NASA SP-5081

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AN AEC-NASA TECHNOLOGY UTILIZATION PUBLI

ADVANCEMENTS IN TELEOPERAT SYSTEMS

A colloquium held at
the University of Denver
Denver, Colorado
February 26-27, 1969

TECHNOLOGY UTILIZATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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1. Remote Control Equipment

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Technology Utilization Division
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Foreword

In 1964 two seminars were held under the title PROJECT ROSE (Remotely Operated Special Equipment). The purpose of the seminars was to bring together, for a sharing of ideas and experiences, those working in the diversified field of remotely operated equipment. The proceedings of the Colloquium presented here successfully laid the ground work for future meetings of this kind.

Since 1964 the term "teleoperator" has come into wide usage. A teleoperator, in the broad sense, is a device which extends man's ability to accomplish work. It enables him to operate in remote areas and dangerous environments, or it amplifies his work capacity. In the field of prosthetics, a teleoperator restores dexterity to man or provides him with it. The modern teleoperator became essential with the advent of nuclear energy, where mechanical arms are indispensable for handling radioactive materials in hot cells. Teleoperators are the product of development over many years and, as these proceedings show, their use in connection with radioactive materials remains one of the most important areas of application. However, it is by no means the only one. In space and undersea exploration, artificial limbs, and numerous other devices are increasingly included in the scope of teleoperator systems to improve man's capabilities. Advances in computers, television, and electronic and mechanical devices have contributed to the widespread use of the teleoperator. These advancements and applications were fully discussed at this latest Colloquium, and are generally the substance of the proceedings.

In fact, the purpose of the 1969 Colloquium was the same as that of the earlier seminars. Its sponsor, the Technology Utilization Division of the National Aeronautics and Space Administration, felt that the best results would be achieved if proceedings were held informally in a relaxing atmosphere. The meeting took place on February 26 and 27, 1969, at the University of Denver's Lawrence C. Phipps Memorial Conference Center. The attendance was limited to seventy and was by invitation only. Of the seventy attendees, thirty-two were on the speaking agenda and all participated in the discussions.

We, the cochairmen, appreciate the cooperation of these interesting participants and thank them for making the Colloquium a stimulating and productive experience. Meetings of this kind serve a very real purpose and it is expected that similar ones will be held in the years ahead.

FOREWORD

The participants will also note that the remarks of some of the speakers recorded in these proceedings do not appear in the same order as they were actually presented at the Colloquium. These changes were necessary in order to expedite the preparation of this document. They were made in such a way, however, as not to lead to misunderstanding or detract from the informative value of the material.

Edwin H. Johnsen
Washington, D.C.

Charles B. Magee
Denver, Colorado

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DISCUSSION LEADERS

THE FIRST DAY OF COLLOQUIUM

The 1969 Colloquium on Advancements in Teleoperator Systems convened in the Lawrence C. Phipps Memorial Conference Center, 3400 Belcaro Drive, Denver, Colorado, Wednesday, February 26, 1969, at 9:00 a.m. with Charles B. Magee, University of Denver, and Edwin G. Johnsen, AEC/NASA Space Nuclear Propulsion Office, Cochairmen of the colloquium, presiding.

CHAIRMAN MAGEE: Ladies and gentlemen. I would like to welcome you on behalf of the University of Denver to this colloquium on teleoperators. We in the university business are supposed to disseminate good information, and I think we will do that today and tomorrow. I want to emphasize the flexibility of the agenda for those of you who have something to say. We will have time for open discussion or presentations that we do not have time for today.

The first speaker this morning is a gentleman who will set the keynote for this colloquium, Mr. John Welles, Head of the Industrial Economics Division of the Denver Research Institute.

MR. JOHN WELLES: I am substituting for Ron Philips, Director of the NASA Technology Utilization Division, who is unable to be here, but I am happy to have an opportunity to talk with you. For someone like myself, who has been in what we call the technology-transfer business, this meeting should, I think, be an exciting interchange of ideas.

First, you are in a developing technological field and it is always stimulating to be on the forefront of a new technology. Second, in this room, I would guess, there is the predominant proportion of expertise in the nation, if not in the world, in your field of technology. Third, many new applications are awaiting to be tapped. You also have going for you someone outstanding in the technology-transfer business — Ed Johnsen. Mr. Johnsen has acted as a catalyst in bringing you together in meetings such as this to give you an opportunity to exchange ideas and promote the advancement

of your field. I believe that this catalytic role is generally under-appreciated; there aren't enough such individuals serving the technological areas in this country. Finally, your sponsor, the Technology Utilization Division of NASA, has had more experience than any other organization in the world in trying to match market needs with technological capabilities.

There are two main purposes of this meeting. First, it provides an opportunity for the leaders in your field to exchange information on what you are doing and to get caught up from your prior two meetings. Second, it offers you an opportunity to generate new ideas for new applications of your technology. I would like to give you some background about what has been going on in the field of technology transfer in recent years. This might stimulate you to better accomplish the second purpose of the meeting, namely, matching your technology with new market needs. I shall use the NASA experience in technology utilization and transfer, since, until about three years ago, NASA was the only organization in the United States that was consciously trying to formalize the process of technology transfer in the broadest sense. Only in recent years have most economists come to realize that economic growth contains the ingredients of technology and management.

It is interesting to note that when the Western European countries compare themselves with the United States, they talk about a technology or a management gap. So I think we are finally beginning to appreciate the contributions you gentlemen are making, not only to the economic growth, but to social progress, and hopefully, to more peaceful international relations. Technology transfer is the name of the process by which technology gets spread around and applied in an economy or in the world. The NASA technology-transfer story started in 1958. That year, the National Aeronautics and Space Act was passed creating the Space Agency, and in it was language which stated that NASA should "...provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

When Jim Webb became Administrator of NASA in 1961, he took this clause seriously. During the next two years, a group of people in NASA Headquarters began an effort to formalize the process of dissemination of NASA's technological results. This was not an easy task because there was no model to follow. Nobody had tried to do this in a broad sense before. In 1963, however, based on NASA Headquarters'

effort, Mr. Webb formed the Office of Technology Utilization and launched the NASA Technology Utilization Program. Among other things, he appointed Technology Utilization Officers at each NASA Center. It was their job to comb the Center to find new technology that might have application elsewhere in the economy and to put it into the pipelines, the dissemination pipelines, in the nation. The program gradually developed some objectives and a philosophy.

Currently, this program has four major objectives. First, to increase the return on the national investment in aerospace R & D by encouraging other uses of this technology. Second, to shorten the time gap between discovery of new knowledge and its application in the marketplace. This time lag is of concern to economists who deal with science and technology. Third, to aid the movement of new knowledge across industrial, disciplinary, and regional boundaries. Coming from a university, I can say that probably the worst offender in this respect is a university, with its artificial boundaries between the departmentalized disciplines. The final objective is to improve the means of transferring new knowledge to its points of eventual use. This is the complex process by which you gentlemen acquire new technology that you are not developing yourself.

Part of the NASA philosophy is its belief that a government agency can make major contributions by learning how best to encourage the use of new knowledge generated at public expense. In other words, let's give the taxpayer the full benefit of the money that he has spent on the mission-oriented activities of NASA. Another bit of philosophy expounded by NASA is that those who create new knowledge have a responsibility to disseminate it. Consideration should also be given to every channel of transfer, since people who can use these ideas or research results do not always read the right journals. To encourage those who create knowledge to accept responsibility for disseminating it, NASA has instituted new technology clauses in contracts with major R & D contractors. These require contractors to report any new technology, innovations or inventions they may develop during the course of their NASA-sponsored work. Employees in the various NASA research centers also are expected to observe this requirement.

In addition to these measures, NASA has embarked on a variety of activities to implement the Space Act language quoted earlier. First, it has sponsored basic research on how technology gets transferred around the economy. At this point it appears that one of the most effective means is

person-to-person communication. The present meeting is a good example. Second, NASA has sponsored a variety of meetings on the technology transfer process to stimulate interest in improving the process. Third, the largest activity in terms of dollar expenditure is the NASA publications program, with which most of you are familiar.

Each year, NASA publishes hundreds of its R & D contract reports. These, together with other worldwide aerospace research reports, are indexed and abstracted semimonthly in the publication STAR, the Scientific and Technical Aerospace Reports. Dovetailing with STAR and coming out semimonthly on alternate weeks is "International Aerospace Abstracts," which NASA also supports. This reports on the worldwide published aerospace literature. In addition, NASA publishes Technology Surveys. When the Space Agency feels that it has made a sufficient contribution in a given field of technology which should be more readily available to interested people, the Agency commissions a Technology Survey. The one I am holding up now "Teleoperators and Human Augmentation, SP-5047", which happens to be in your field, is a joint effort by AEC and NASA. NASA also puts out Technology Utilization Notes covering various fields of interest to the NASA mission. Here is one entitled, "Batteries for Space and Power Systems."

Among more extensive publications is the NASA Tech Brief Program. This is simply a reporting of one or two pages of little tidbits of technology or the genesis of an idea that has been developed by a NASA contractor at a NASA Center. These are given wide circulation, and where a Tech Brief is not self-sufficient, it includes a note inviting the reader to contact the Clearinghouse for Federal Scientific and Technical Information and get what is called a more detailed Technical Support Package. NASA also puts out translations of significant foreign documents and makes these available to contractors. Here is a technical translation of a Russian research report on aircraft navigation.

In an attempt to control the publication problem, NASA has developed on an experimental basis what are called Regional Dissemination Centers. At present, there are six such centers around the country. These centers house computer tapes provided by NASA Headquarters that index the NASA literature. About 6000 items per month are added to these tapes. At Indiana University's ARAC (the abbreviation for the first regional dissemination center), for example, industrial firms pay a fee to subscribe to the Center's services. One of the services is called a Current Awareness Service. Each month the regional dissemination center

searches its new tapes for documents which match the interest profile of the subscriber. The subscriber gives to the regional dissemination center (RDC) enough information so the center can work out what is called an interest profile of the key words that indicate the needs of a company. Each month those key words pull out the indexed documents in the system. Relevant abstracts go to the subscriber. Then, if the company wants to order an entire report, it can do so. These, for the most part, are reproduced from microfiche right at the center.

The centers also perform retrospective searches for subscribers. If a company has a problem, it gives enough information to the center so the staff can key-word the problem into the data bank and search for relevant documents. These are sent to the subscriber. The following are examples of the transfer of space technology to commercial or civilian use.

Figure 1 shows two photographs of lunar rocks. The right-hand photograph is the raw one, transmitted from the moon. The left-hand photo is what the original looks like after processing by the Jet Propulsion Laboratory, which has developed a computerized technique for increasing the resolution of photographs.

In figure 2, the left is a normal X-ray of a human skull. On the right is the same X-ray after it has been processed by this computerized technique. You can see how the blood vessels stand out for greater ease of study by a doctor. The system will not produce anything that is not already on the film, but it does increase the resolution.

Figure 3 illustrates a rather sensitive instrument that was developed for detecting micrometeorites, sufficiently sensitive to detect the drop of a grain of sand from the height of one centimeter.

Figure 4 shows how part of this instrument has found nonspace application in the medical field. By strapping it to a human finger, it will record involuntary muscular contractions, which are an early warning of Parkinson's disease, long before it can be detected by conventional methods.

A final example is shown in figure 5 — an astronaut's helmet. In figure 6 we see how this helmet, with slight variations, is finding use in tests on respiratory and metabolic activities of humans. It is a more accurate device than the ones previously used and far more comfortable.

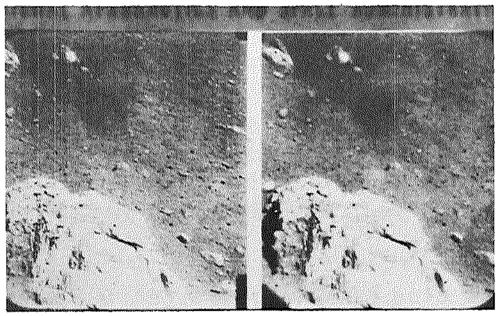


FIGURE 1

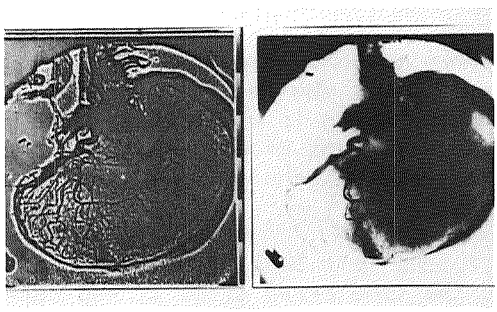


FIGURE 2

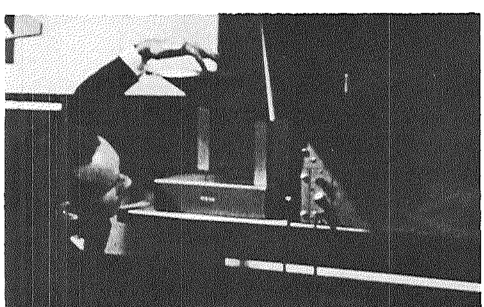


FIGURE 3

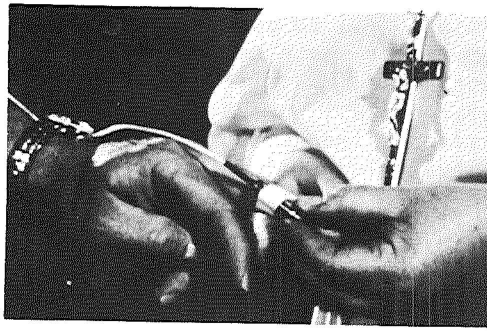


FIGURE 4

FIGURE 5

FIGURE 6

NASA has documented hundreds of such transfers, mainly for two purposes: (1) to convince the skeptics that technology—developed for space can and has found use in the commercial world and (2) to try to learn more about the technology transfer process so that transfers can be stimulated. A lot remains to be learned about the transfer process. Some people have tried to justify the space effort on the basis of spin-off, fallout, by-products, or secondary impacts. A more realistic view is that as long as we have a space program, let's get the full benefit of the technology that is developed for space by encouraging transfers to nonspace applications.

The Atomic Energy Commission has recently instituted a formalized technology-transfer program. The Small Business Administration is in the process of developing a program, the Department of Commerce is getting on board, and the Department of Defense is also beginning to become active in the field. One of the more significant developments is that Congress has become quite interested in technology transfer, particularly as a mechanism for helping small business.

To summarize, the opportunity provided by this colloquium for you to exchange ideas, as you have twice before, should be productive. We hope that you will make use of the opportunity to generate new thought about how to contribute from your store of knowledge to other fields of endeavor. It is not easy to do, but I hope this exposure to NASA's Technology Utilization Program will give you encouragement to try harder. Don't hold back on ideas. Charlie Magee mentioned it is going to be an informal meeting. If everybody operates under this ground rule, you will have fun being exposed to a lot of ideas. I wish you success, and in closing, I shall pass out a pamphlet that briefly describes the NASA Technology Utilization Program which you may wish to take home with you and read at your leisure.

CHAIRMAN MAGEE: Thank you very much, Mr. Welles.

At this point I would like to turn the meeting over to the permanent Chairman, Mr. Edwin Johnsen.

CHAIRMAN JOHNSEN: I would like to thank Mr. Welles for his welcoming speech. I would like to point out, though, that this particular session isn't solely a NASA technology transfer to the outside. We have a lot to learn from the other disciplines represented here. Before proceeding, I would like to welcome all of you and especially our three guests from Europe: Mr. Mettetal from France, Mr. Vertut from France, and Dr. Kleinwächter from Germany. We are very

glad to have you here. I would also like to introduce Mr. Snyder, one of the people most instrumental in holding this meeting.

To continue, since we want to emphasize interaction, we have discouraged formal papers. We hope that you will keep your comments to the point. I think you can assume that everyone here is a highly qualified technical person. You can report what you have done within the last two or three or four years. We would like to have you start out that way, then ask questions and make your own comments. I think we need interaction. Draw information out of the speakers. This is the whole point. I would like to ask our first speaker, Mr. James Allen from Rancho Los Amigos Hospital, to discuss his work on manipulators.

MR. JAMES ALLEN: I will try to be as informal as I can. Briefly, Rancho is a chronic disease center which deals with paralyzed people. My particular forte is orthotics, or braces. We attempt to rehabilitate paralyzed people by putting motorized braces on them and then devising some scheme whereby they may control them. I believe a quicker introduction into what we are doing can be told by the film we have. What we are showing here is a young lady who had been paralyzed for about eleven years, on the flat of her back before we cured her. What we did was to put her in an electric wheelchair. She drives it with the tongue switch shown in the upper part of the film. We also put a motorized arm brace on her. This too she controls with the tongue switch. What we show here is a small residual motion that she has in her left hand. It is not useful except to operate the switch which alternates the control from her wheel chair to her arm. She can either drive the wheelchair or use the arm, but not do both at the same time. This film was taken after about nine months of training. Also, it is amateurish and she is a bit nervous and may spill some milk here. These are toggle switches she is flipping back and forth. This apparatus (fig. 7) was made a little over four years ago, and the girl, along with some twenty others, is still using it. She gets up every morning — and the reason I am saying this is to try to add some evidence to the usefulness of the gadgets — she is moving the tongue switch out from the front of her head with a head switch. I will cut the film here. It's enough to give you a little introduction. If you want to see the rest later we will certainly show it.

Now, along this same line we had a notion that victims of certain neurological diseases, stroke in particular or

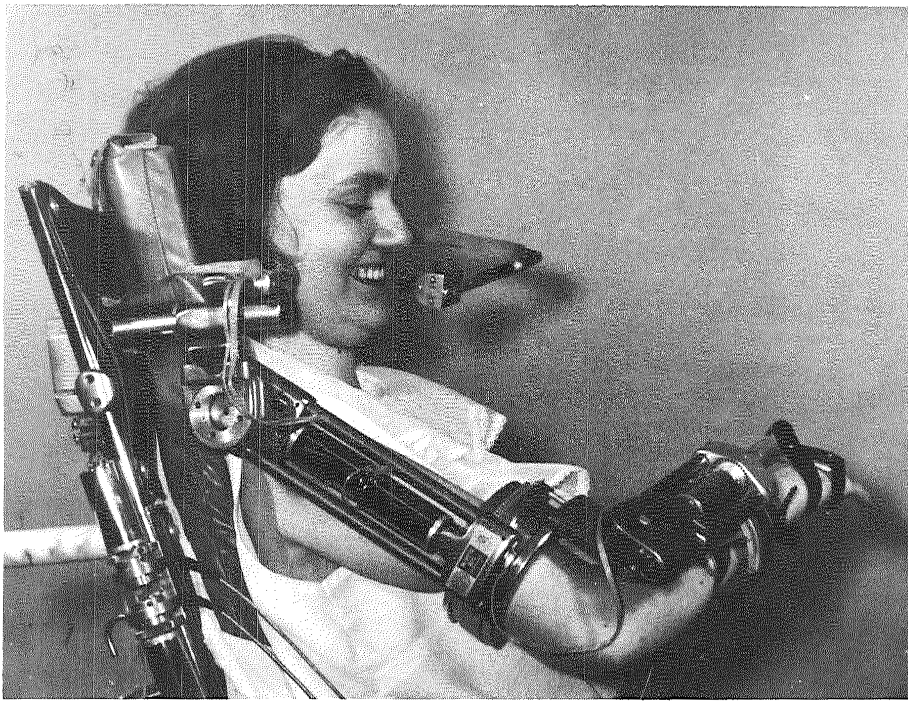


FIGURE 7

cerebral palsy, could be helped or they could be retrained if we exercised the patients manually. We felt that a programmed arm brace would do this, so we built one similar to the one used on the paralyzed patients. It was a master-slave type of brace. I would like to show you the gadget we have mounted to a table here, then invite comments or any questions.

This is the master brace; it is the control brace for the slave. I will try to make it do something. We invite anyone who wants to, to play with it (figs. 8 and 9). This is a parallel-jaw grabber with a wrist motion. We also built a powered hook and this is it((figs. 10 and 11). This is the arm that you saw in the movie, the same type of thing but a little smaller and not quite as strong. It is an orthotic device — which means that rather than replacing the limb we are bracing a paralyzed limb already there. This particular device is not meant for day-to-day use. We built it as an exercising device. We also arranged it so that we could program motions on tape (predetermined specific motions) and then play these tapes as many times as we wanted. Our notion was that we would attempt to improve the condition of spastic individuals so that they could make specific motions easier than before. This is a retraining process of the neurological paths.

QUESTION: Was part of this also maintenance of conditioning so that if positive action resulted there was a regain and the muscles would be in good shape to be used?

MR. ALLEN: That is what NASA and other people would call spin-off benefits. What we claim is that our device gives a range of motion — exercise therapy, if you will.

QUESTION: In using the initiating controls on this device, does the patient decide which routine exercise he will go through, or is this something that is selected by somebody else?

MR. ALLEN: The selection is made by a therapist, at least at this time. We are quite new at this sort of thing. I think I can't really report results yet because, as I say, this is a theory; we are not absolutely sure that it is correct.

COMMENT: Could I make one comment? It could be volitional if you were speaking of exercising a patient who was unilaterally affected. The idea is that one arm could exercise another, reinforcing bilateral patterns of activity.

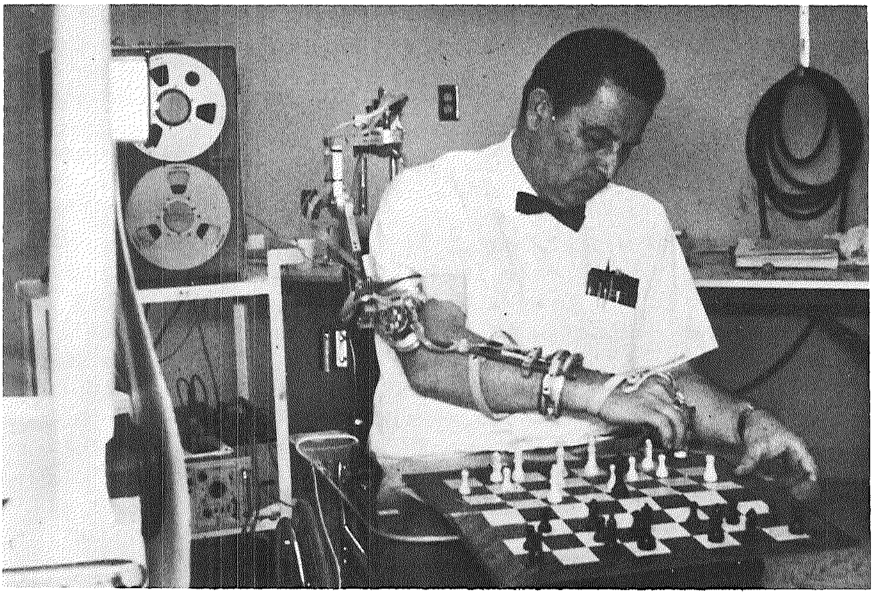


FIGURE 8

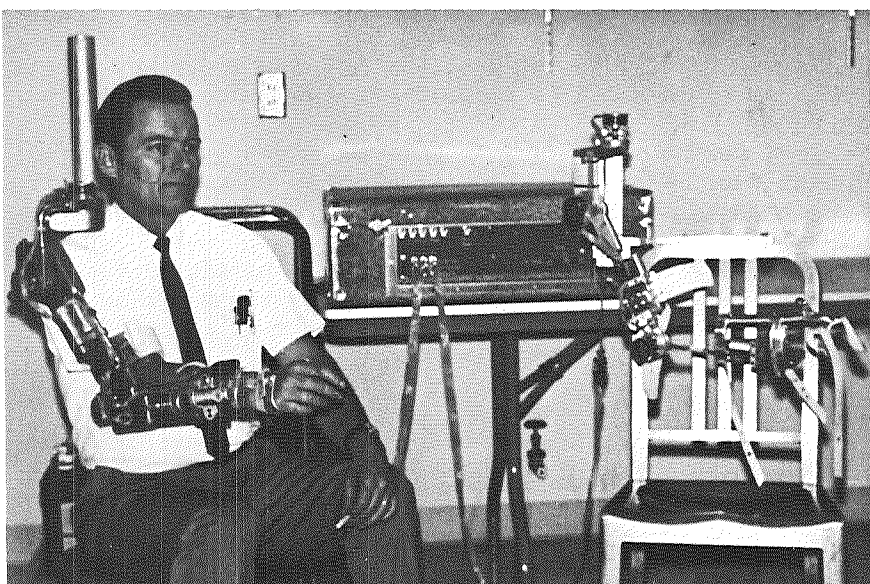


FIGURE 9

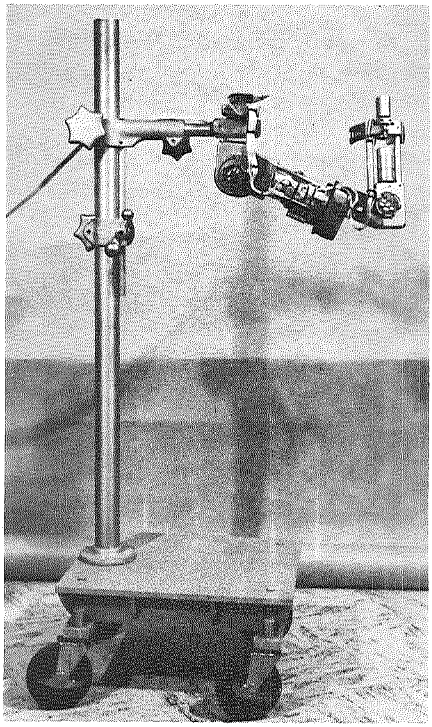


FIGURE 10

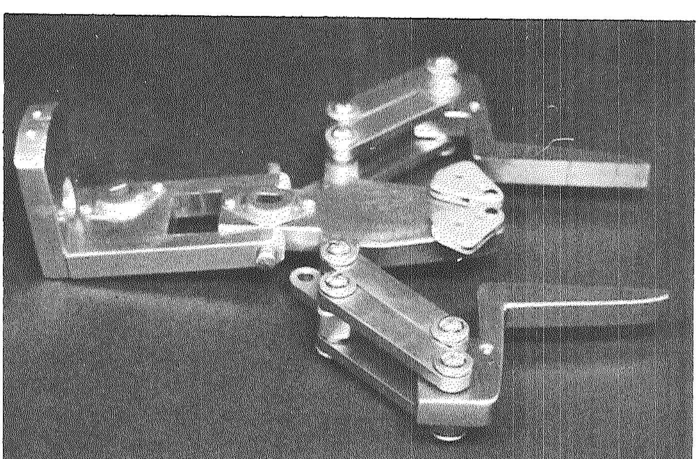


FIGURE 11

MR. ALLEN: Yes.

QUESTION: In terms of technical relations, are you trying to rechannel a person's neurosignalling system through this type of training?

MR. ALLEN: Yes, we are. Our reasoning is based on clinical experience. Therapists do this now, and they get results.

CHAIRMAN JOHNSEN: Mr. Allen, would you care to give us some idea of what these things cost?

MR. ALLEN: As a single unit, this particular one would cost about $6000; as a bilateral unit, $12,000. Now, what the cost of development is I don't believe I can really say. These things were supported by the Social Rehabilitation Service (SRS) or the Vocational Rehabilitation Administration (VRA), the old organizations, and the present National Institute of Health (NIH) under grants to Rancho, which were handled by the Attending Staff Association. We have probably, in our whole program, spent around a million dollars over ten years, but of course there are many other things in addition to this gadget.

QUESTION: Do you have any literature on this?

MR. ALLEN: Yes, I have the orthotic reports we have made to government agencies; I also have some very sketchy specifications that tell what each joint will do and what it is.

QUESTION: I wonder if you could just briefly outline what the servo system is in the potentiometer sense?

MR. ALLEN: Very simple. Permanent magnet motors drive the arm. Potentiometers monitor the master and the slave, while we measure the error between the two. We then present this signal to an amplifier whose output is a relay, that drives this motor of this slave. This is not a proportional system; it is on and off as shown here.

Since we are on the subject, what I will attempt to do is to move the joint at a very low rate. What I am showing you is a proportional control system. Can you see it moving? It is moving and I am trying to show that you can do very fine manipulations if you desire. My battery is about dead. I could go a little faster if I had more juice. We are using

12-volt motors that draw about 200 mA and I want to give credit to John Schwartz, who is standing beside you. He worked on the amplifiers and did a great job.

QUESTION: What kind of amplifiers?

MR. ALLEN: I showed two different things. A transistor dc amplifier, I believe. The master-slave is a single-speed relay closure type of amplifier. You can use either a proportional or a contactor system.

COMMENT: In the master-slave there seems to be a certain jerkiness to the motion.

MR. ALLEN: I didn't have a dither signal on here, but you can smooth it out by putting a little dither in the circuit.

QUESTION: Do you always use one-to-one ratio between the master-slave?

MR. ALLEN: We are doing so now for a specific reason. A one-to-one ratio was the only proportion that would fit on an arm.

COMMENT: I was just curious, if you have to repeat it a couple of times before you construct it, if you put a multiplier on it, then his motions would all be slower.

MR. ALLEN: I think you could have any ratio you wanted. There would be no problem in setting that up. We just did it one-to-one.

QUESTION: How much load can you put on the end of the slave arm?

MR. ALLEN: Ten pounds is the maximum on this particular gadget. I think, within limits, you could probably design one without increasing the size too much, maybe increasing the payload up to 20 pounds.

COMMENT: Mr. Allen, perhaps some of these people may be interested in your tongue control.

CHAIRMAN JOHNSEN: I think we need to limit our discussion to manipulators right now. We will bypass the tongue control until we get to sessions on controls. I would like to keep on going. I will now call on Carl Flatau

from Brookhaven National Laboratory, who has been working on a different version and a master-slave.

MR. CARL FLATAU: I would like to concentrate my remarks on a segment of teleoperator technology and applications, a segment I prefer to call "telemanipulator technology," as the word "manipulate" seems to imply "operating with skill and dexterity." I would furthermore like to take the prefix "tele," meaning "far off," quite literally and concentrate on systems at least designed to operate over considerable distances.

Our aim from the start was to satisfy the needs of high-energy particle accelerators (or atom smashers). About six or seven years ago particle physicists realized that not only were ever-increasing particle energies required in order to further probe the structure of so-called "fundamental particles" but also vastly increased beam intensities or beam currents were absolutely essential in order to yield useful data on weak interactions and other rare events. Accelerator builders had by that time developed the technology to supply these increased intensities. Of course there were still a number of problems to be solved, one of which was concerned with the fact that the high intensity particle beams induce radioactivity in the accelerator components which, even after shutdown, is of sufficient intensity to severely restrict or entirely preclude human access. There are many ingredients to the solution of the maintenance problem involved, one of the very essential ones being the use of a highly dexterous telemanipulator system.

Since typical accelerator structures are narrow tunnels with lengths or circumferences in the order of miles (fig. 12), a larger slave-to-master separation than possible with mechanical master-slave manipulators was required. An attempt to turn the situation inside out (fig. 13) was not possible in existing accelerators like the Brookhaven AGS, because of space restrictions. It also turned out to be awkward and expensive for new installations. The slide shows an LRL mockup built in connection with their design study of a 200-BeV proton synchroton. The extreme congestion often found in the most radioactive areas of accelerators (fig. 14) prevented use of then-existing servo manipulators like ANL Model E3. It was realized, however, that the E3 was the right type of device if it could only be had in a more compact form. Since accelerator engineers have the habit of building what they require and cannot buy or borrow, I did just that.

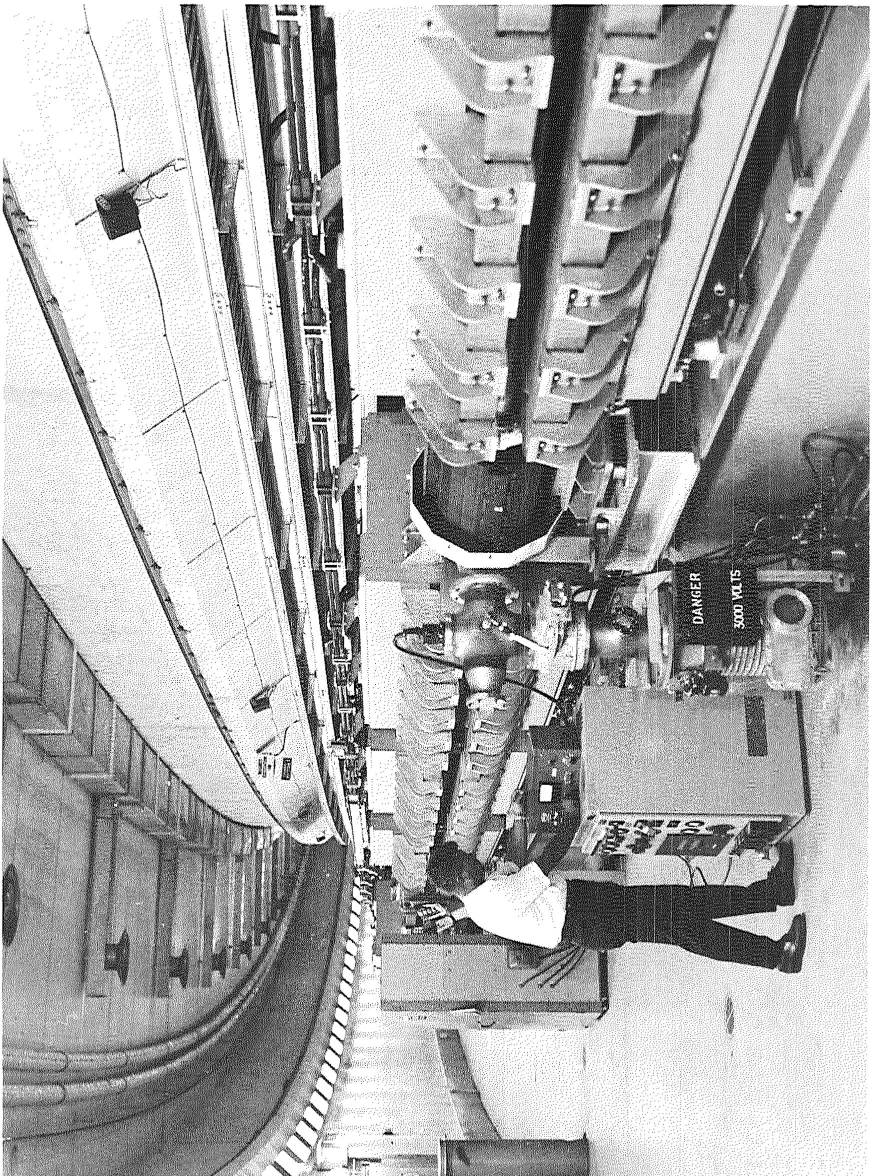


FIGURE 12

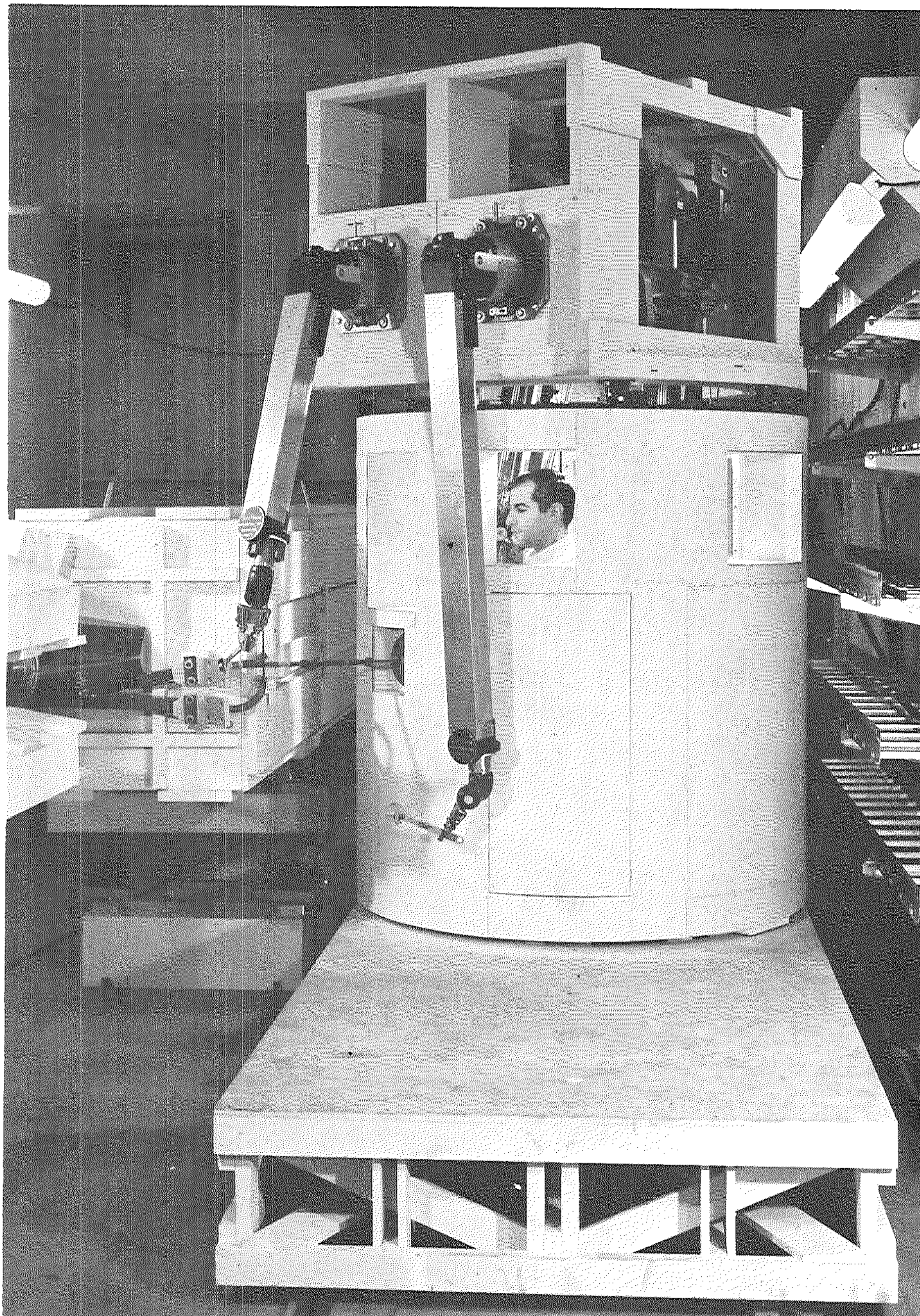


FIGURE 13

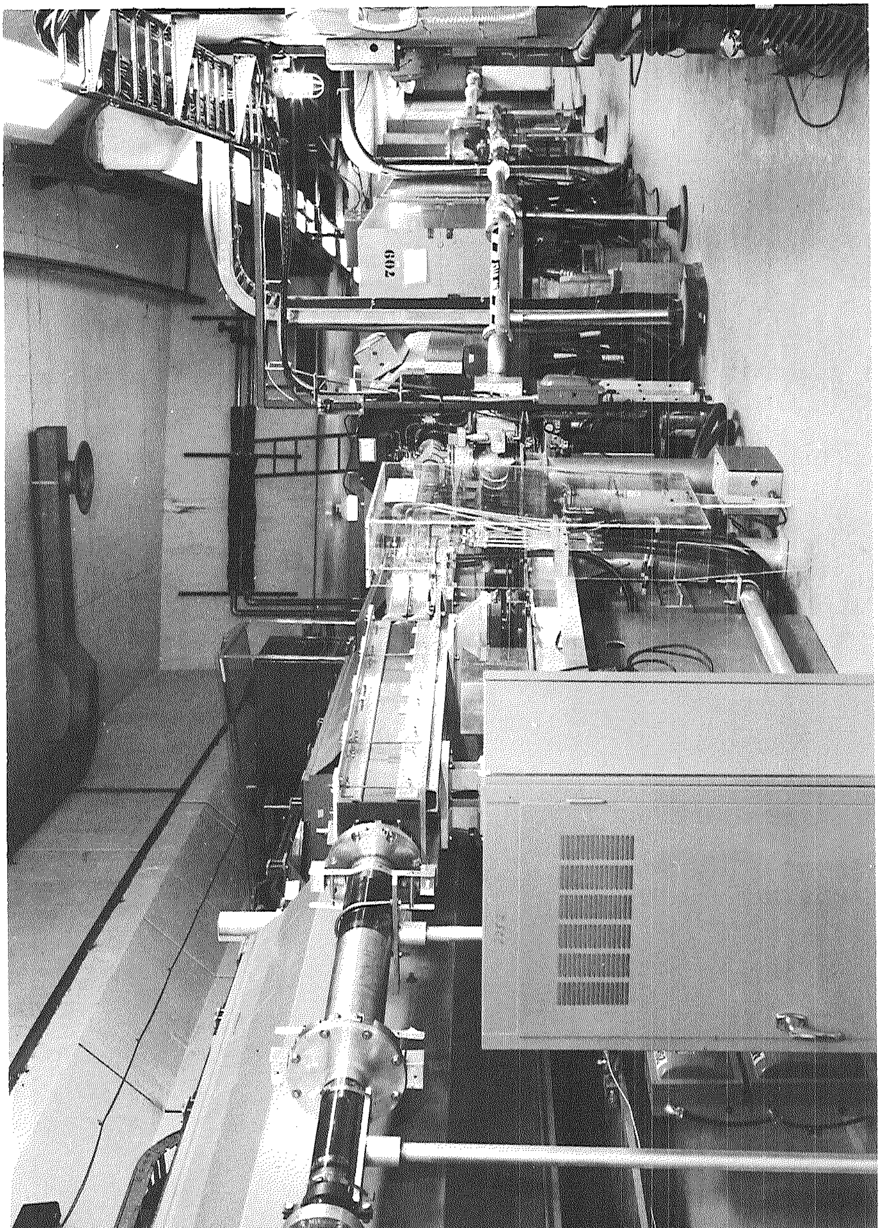


FIGURE 14

FIGURE 15

This slide (fig. 15) shows the single arm with slave in foreground and master behind. I do not recommend the use of a single master-slave arm as these are at their best when used in pairs. However, budget limitations often force us to do things that are far from ideal. The arms are mounted in "temporary" test suspensions which are height-adjustable by hand but have no transport or indexing motions. The cabinet in the background contains the electronics in a test rack. This manipulator has true bilateral force reflection as is usual in master-slave arms. A capacity of 30 lb is nominal. That means that 30 lb can be exerted in all directions with arms at essentially their maximum or near-maximum extension.

Conventionally, seven degrees of freedom are employed (fig. 16). X motion only has been changed for reasons of simplifying counterbalancing and providing better articulation. As long as master and slave are mounted similarly they can be hung from the top or supported from the bottom without modifications.

In figure 17 an attempt is made to show the very large motion range possible. Y and Z motions move through 250 degrees each with respect to the next higher motion. X has a range of 340 degrees. I believe this wide motion range is very important and I will come back to it.

As can be seen in figure 18, the arm is quite compact when compared to the operator. Minimum operating volume is about 1 cu ft, which I estimate to be about a factor of four smaller than the volume required for other servo master-slave manipulators. I do not think the arms can be made any shorter, as one loses the ability to work the master. Incidentally, the manipulator is shown here in its usual master-slave stance. Other positions are possible, as will be seen. With counterweights (striped segments), slave weight is 120 lb. They counterbalance the gravitational forces due to arm weight so that no more than 1.5 to 2.0 oz are reflected at the master. When counterbalancing is changed to passive force linkages, the weight will be reduced to 60 lb. As no structural design refinements have been used, slave-arm weight can easily be reduced to 30 to 40 lb. This is important because the size and complexity of the required slave-transport system is a very strong function of slave capacity-to-weight ratio. The ability of a pair of master-slaves to transfer themselves from one transport system to another is also strongly dependent on this ratio.

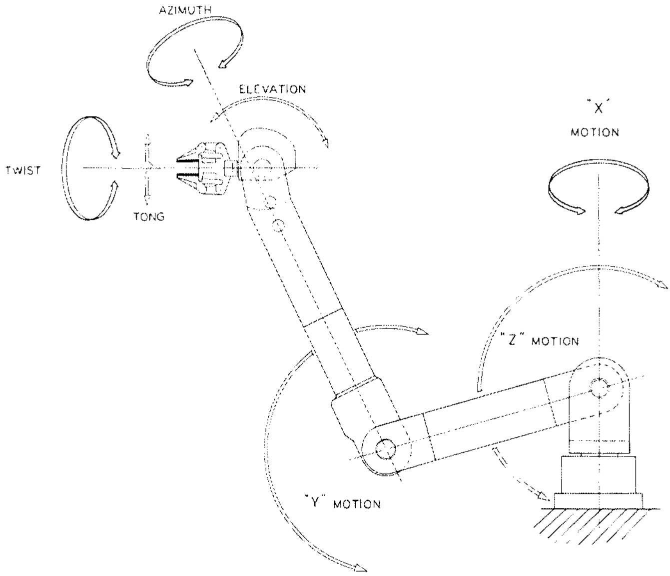


FIGURE 16

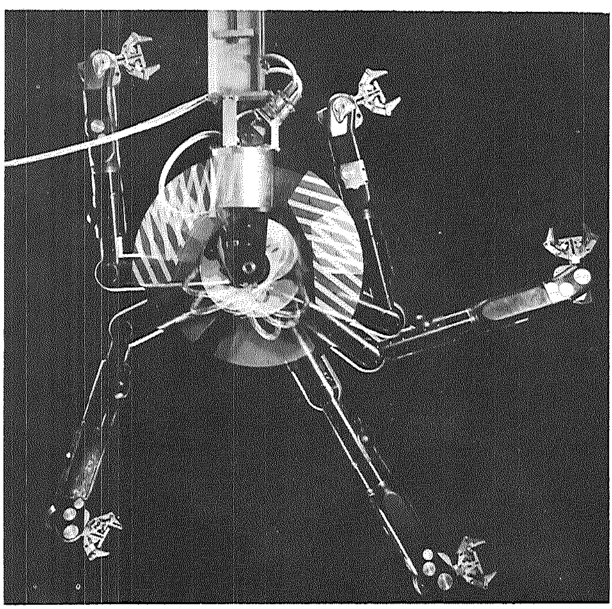


FIGURE 17

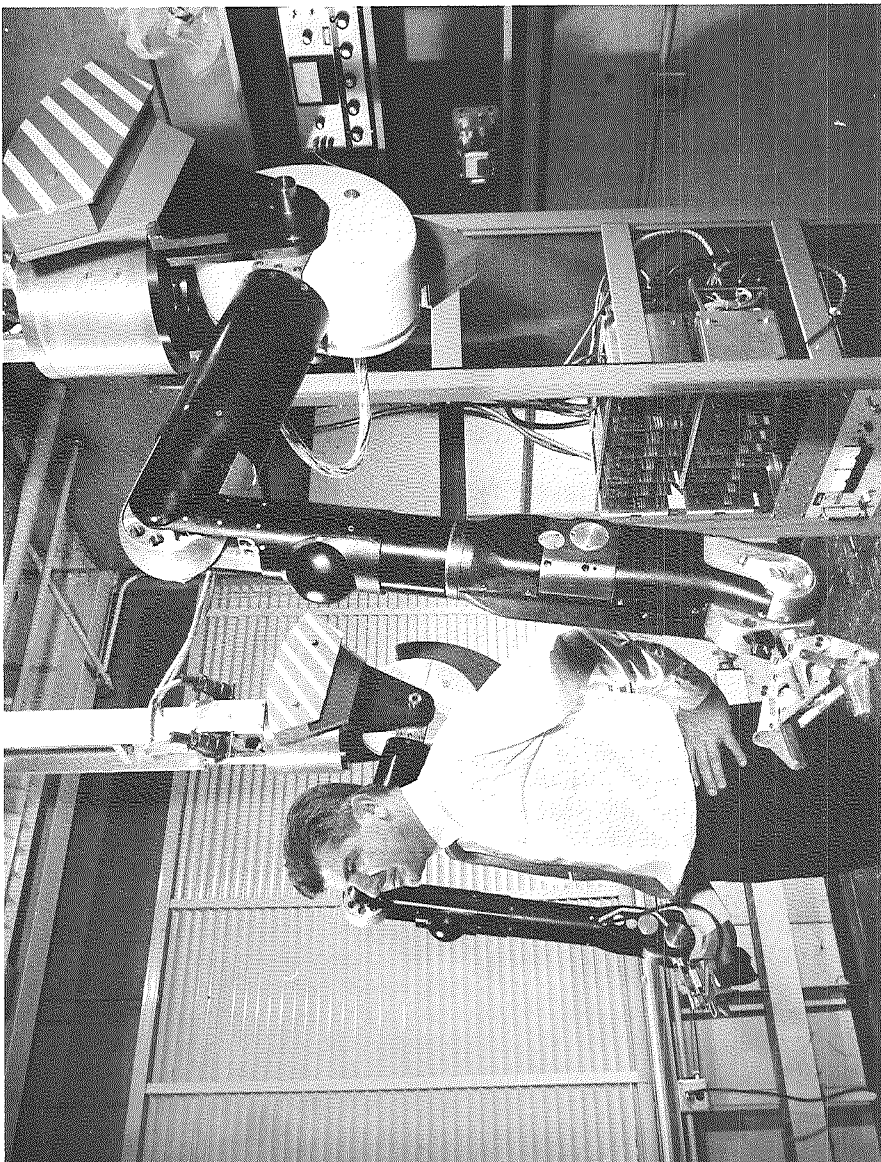


FIGURE 18

Compactness is achieved at the system design level by the use of small dc motors (fig. 19) which fit into the limbs of the arms themselves (fig. 20). Harmonic drives are used for speed reducers of the translational degrees of freedom. These are not quite as efficient as a spur gear reduction unit could be, but the servo system helps us to compensate for this.

To allow for higher friction levels and larger inertias, as well as lower reducing—unit efficiency, an asymmetrical position-force servo scheme is used (fig. 21). Both master and slave have two transducers, a position transducer, and a force transducer. The slave arm is driven from the position error while the torque error drives the master. This system has the property of dividing the friction and inertia components on the motor side of the force transducers by the force loop gain. The result is that friction levels are two or three ounces and reflected inertias are equal to or lower than in other servo manipulators.

Since it is difficult for an operator to exert forces of 30 lb at the master, the slave-to-master force ratio has been made variable (fig. 22). This force ratio is not switchable but varies as a function of input force, as shown on the slide. The system finally used has three segments, as the dotted line shows. Preliminary tests show this to be a good system. It certainly makes interrupting work for force switching unnecessary.

Some other features will be particularly appreciated by manipulator users. The weight of the tong and master handle was counterbalanced in elevation, increasing sensitivity and reducing operator fatigue. In addition to true master-slave twist motion, a continuous twist motion with reaction torque reflected back to master (like a remote torque wrench) is available. The twist-azimuth ambiguity is well known. Simple logic operations sort out motion ambiguity in certain positions, so that with the Brookhaven manipulator, one will not get locked up due to this. An azimuth-X and Y-Z ambiguity introduced by full articulation is similarly handled.

This system has been designed for remote operation requiring electronics near the slave end as well as the master end (fig. 23). For testing convenience all this has been temporarily put in one rack. The panelled sections are power supplies of sufficient capacity to drive a pair of arms. Servo amplifiers, of which two are required per degree of freedom, are in the two bins above, one bin for the master

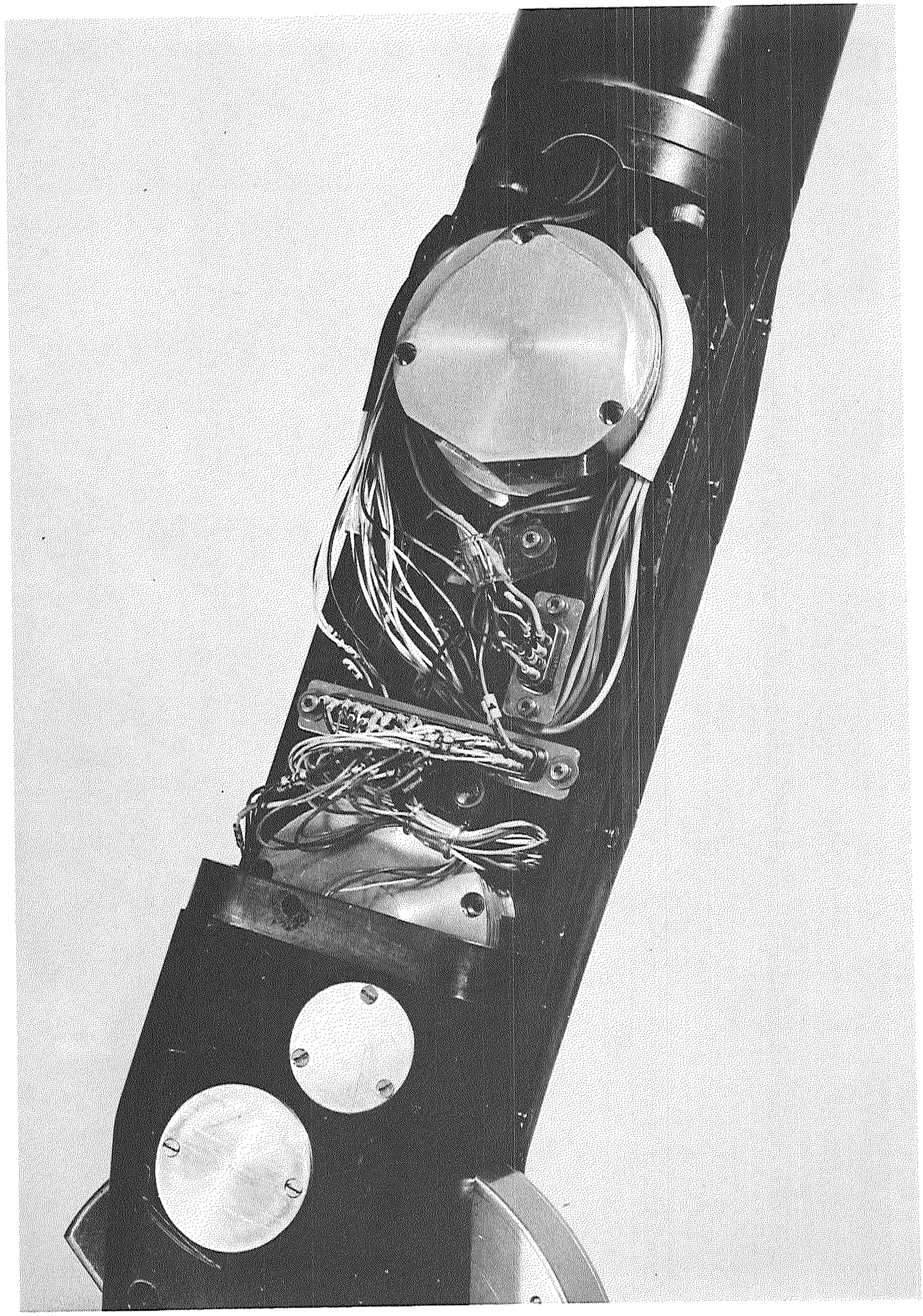


FIGURE 19

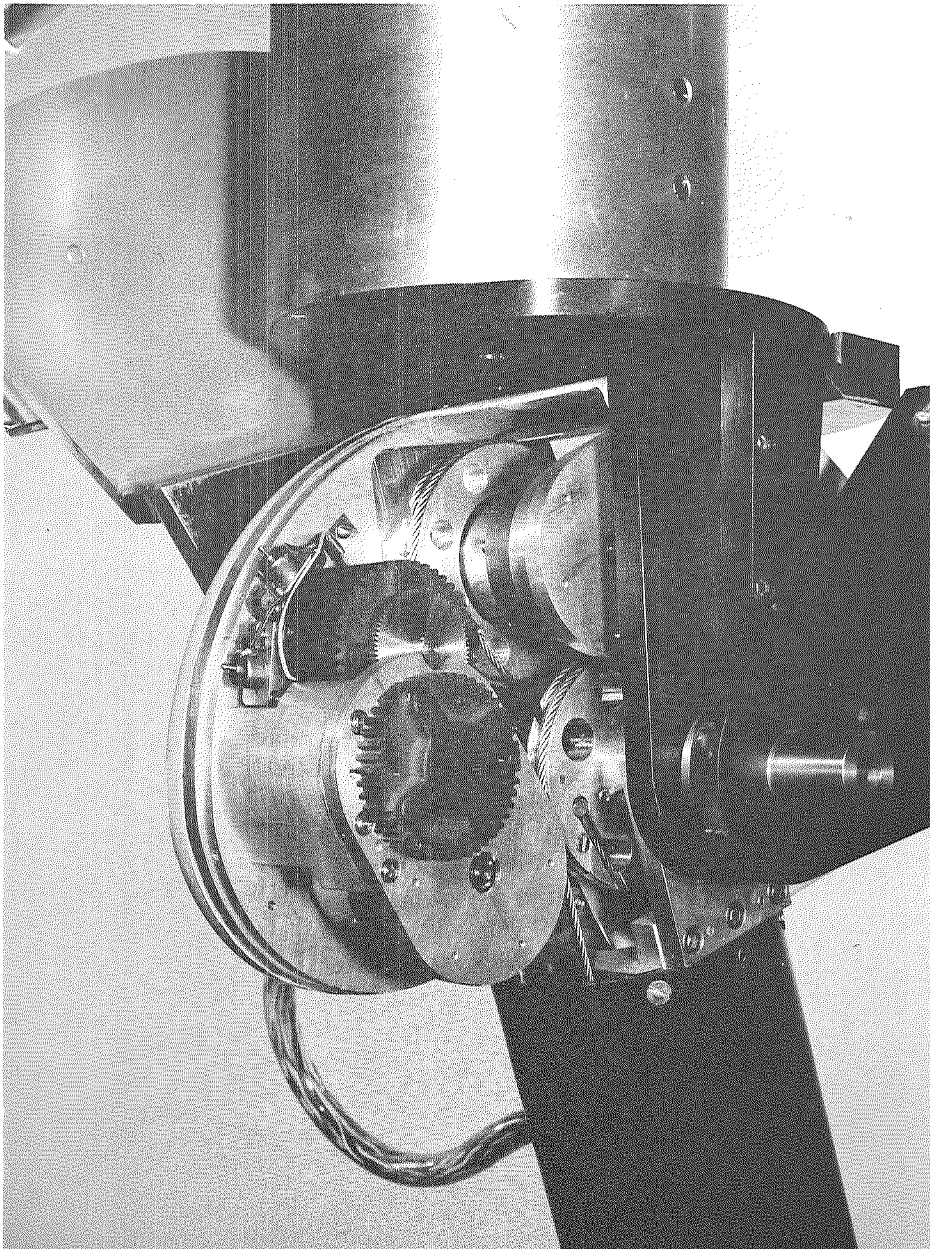


FIGURE 20

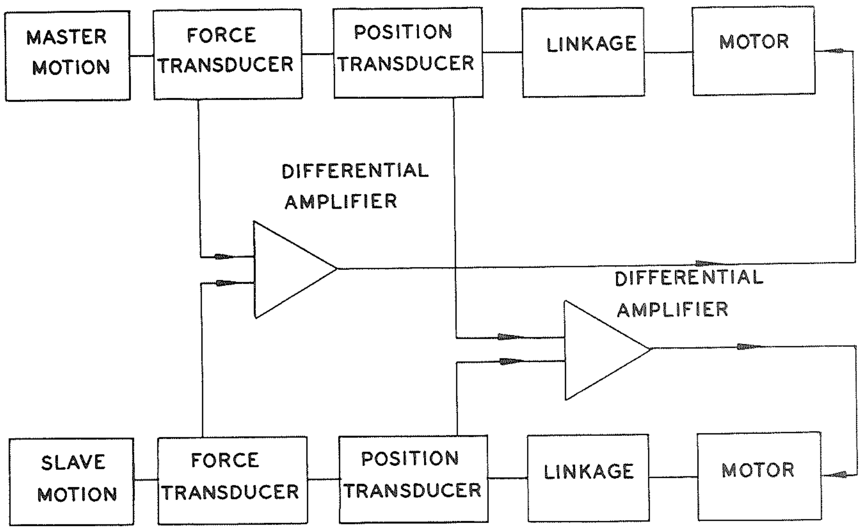


FIGURE 21

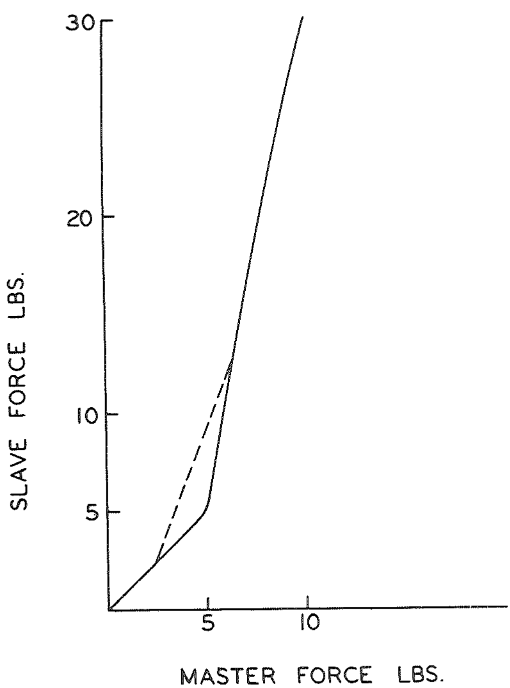


FIGURE 22

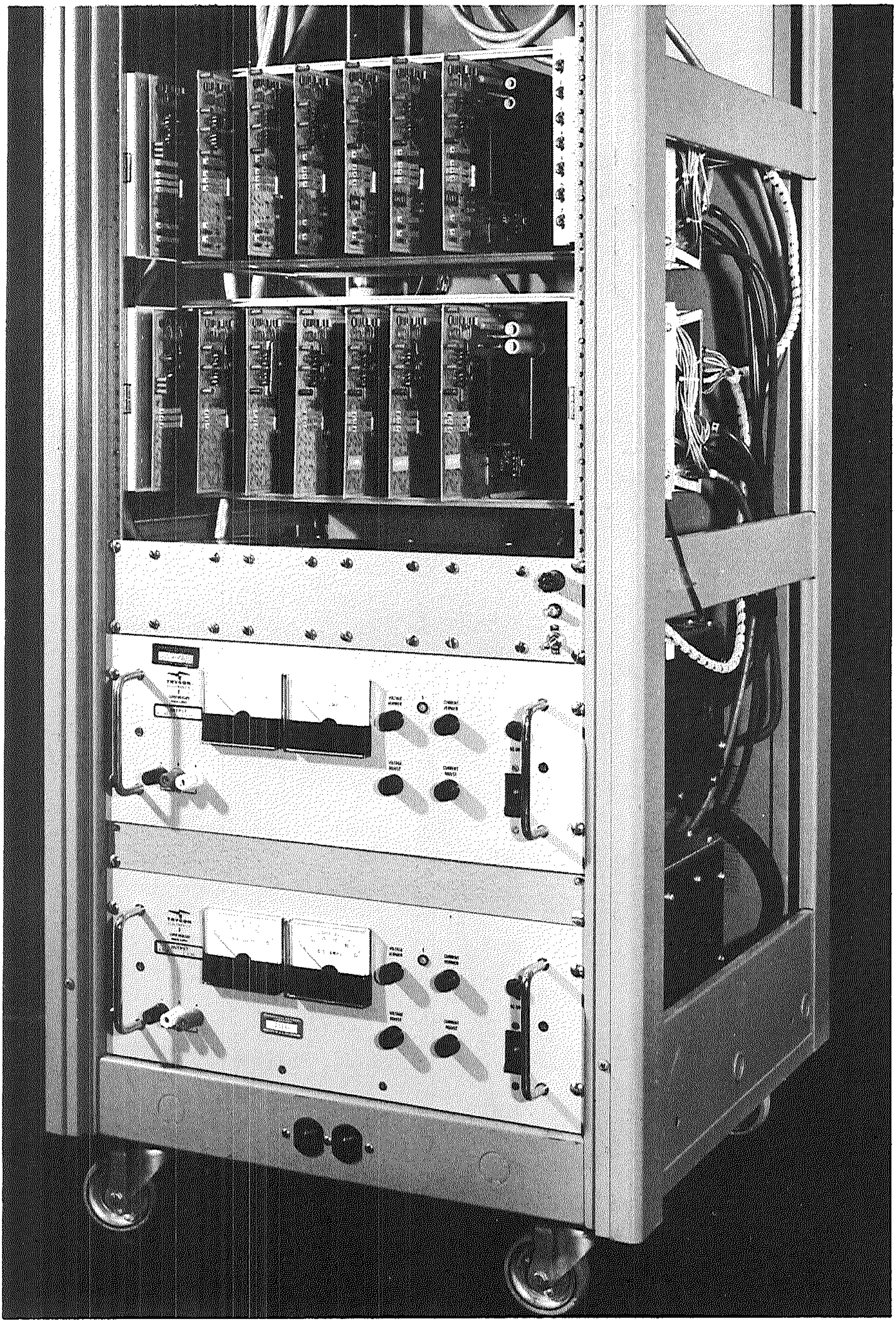


FIGURE 23

and one for the slave. Only 15 low-level signal wires per arm are required between master and slave; there is no other connection between them. The coiled cable in the picture contains 22 wires, this being the nearest Brookhaven stock item. We hope that this setup will be sufficient for distances of 1000 ft or so. Fifteen telemetering channels can fulfill this function just as well and should be used for larger distances. Given the money and engineering time we will do this. The operational setup for a pair of arms will have separate power supplies for master and slave with two bins on each end and 29 communication channels between them. Of course, viewing systems and their motions also will require communications. Notice the bank of seven toggle switches near the master bin. They were put there for debugging purposes and switch-off force reflection on each motion. This can also be used to try a "position only" system without force reflection.

One amplifier board is shown in this slide (fig. 24). Inexpensive, packaged operational amplifiers are used for low-level signals followed by simple power amplifiers. These boards should not be considered more than advanced breadboards. I am sure they can be improved upon in many ways.

The loops on all motions have been closed with satisfactory results. Only recently enough electronics boards became available to try to run all motions simultaneously. Some motions run very well; in others only minimal satisfactory operation has been achieved. In all such cases the reasons are known, and are in no sense basic. A further period of debugging and tuning up must precede further operational testing. In its present form some minor manipulator components and the slave electronics have a radiation damage threshold at about 5×10^7 rad of high energy particles. This is sufficient for initial operation in our environment. These numbers can and will be improved by at least two orders of magnitude. Schemes allowing operation in more severe environments are possible.

Although the manipulator is barely operational, some early tests have been performed. The indications are that improvements in dexterity have been achieved due to the features mentioned. Particularly impressive is the fact that stances other than the conventional basic ones can be tried out (fig. 25). The impression is gained that some of these, like the one shown, lead to more convenient positions for many operations and, therefore, to improved dexterity.

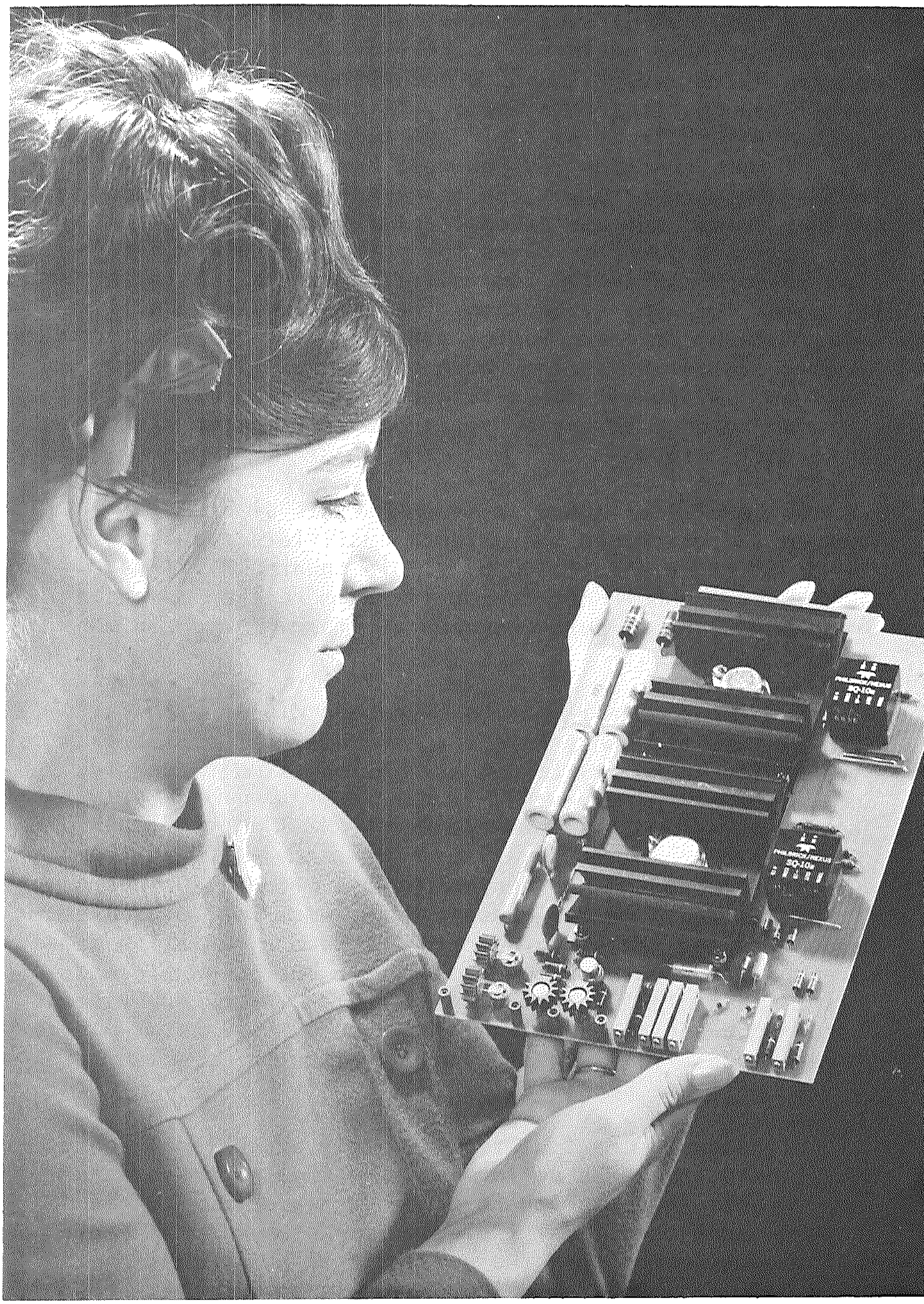


FIGURE 24

FIGURE 25

An apparently marked deterioration of dexterity occurs when force reflection is switched off. Unfortunately no numbers are available yet. One thing is quite apparent — that this manipulator is a very flexible tool for purposes of gathering data and testing out ideas in the area of telemanipulator technology and its applications.

It is intended to use the Brookhaven manipulator extensively as a test bed, at least to the extent that operational requirements allow. Test procedure will consist of several well-defined operations. The time required to perform these tests, via manipulator and directly, will be taken and compared for each operator. From the results, a number called the Dexterity Quotient (DQ), analogous to IQ for the manipulator, is computed by multiplying the ratio of the above-mentioned two operating times by 100. It is hoped that it will be possible to make the tests sufficiently universal and representative to be applicable to most remote-handling situations. Thus, with the same operator, one can use the DQ test to obtain data on manipulator-parameter influence on dexterity. For this purpose the Brookhaven servo manipulator is admirably suitable, since many parameters like force reflection, large articulation range, friction level, tong counterbalance, and continuous twist can be changed or eliminated with ease. It is hoped that a great deal of useful data can be accumulated on these points. It is also hoped that consistent and repeatable results can be obtained with the DQ test even among different operators. If this is so, the test might be used more generally for the purpose of comparing manipulator capability.

The Brookhaven servo manipulator has the minimum seven degrees of freedom. Three distinct ambiguity positions can occur due to the fact that motion excursions are not limited to prevent these positions. It has been found that very simple logic systems can detect ambiguity position and determine which motion should have preference. The other motion is then prevented from moving by artificially increasing the friction in that range. This technique points the way to the introduction of more than the minimum number of degrees of freedom in true master-slave fashion, with a very modest computer, or a small part of an existing larger one, interfaced at the master sorting out the ambiguities. We can use ambiguity motions this way without the need of an exoskeleton.

This would be a first step. Our aim is to eliminate the clumsy master arm. I do not know whether this is possible but I am bringing it up in the hope of receiving some comments

from people working in the field. The question is: if we can detect, encode, and use myoelectric signals to drive a powered prosthesis, does that mean that we should be able to learn how to create and transmit to the muscle a signal which will make the muscle experience a kinesthetic force? If we can do this, a glove-like device worn over the arm equipped with electrodes and position transducers is all the master we need. The position transducer portion of this has been demonstrated by the CRL servo-pneumatic hand.

In the course of development of a sophisticated system one gains insight into its workings. These lead to many ideas and concepts which cannot be incorporated into the system at hand. One feels one really only knows how to design and build a system after it has been completed. The recent exercise of developing a compact servo manipulator at Brookhaven is no exception. I feel compelled to use this audience to air some of these concepts, despite the fact that I am aware that many of them must have occurred to you. But the hope is to arouse some discussion, and if we succeed in throwing new light on even one aspect of teleoperator technology I would consider the exercise worthwhile. The result might well be some of the technology utilization Ed Johnsen mentioned previously.

The information that needs to be exchanged between master and slave, in order for the manipulator to function, is done via a communication link. The fact that this master-slave information transmission or communication link has overwhelming influence on many fundamental manipulator parameters is obvious. The reason it is not discussed more often might be that the overwhelming majority of remote-handling done today is really shielded handling over distances of a few meters. The advantages are that direct mechanical communications and direct, though somewhat filtered, vision is possible. Some servo manipulators have been operated up to about 100 m. For such distances one may use electromagnetic, ultrasonic, or fluidic signals. All servo energy may be transported over such distances without undue losses. When slave-master distances become larger than 1000 m, up to distances approaching 10^5 km, the information link becomes a major problem. This is also true for shorter distances when the slave unit must be transported within a large enough volume. Under such conditions one has to reduce communications to the necessary and probably sufficient two channels per degree of freedom. This is why the Brookhaven manipulator requires only 15 communication channels — seven degrees of freedom, requiring 14 channels plus one auxiliary control channel.

Another example for such a system might be an orbiting, servo-manipulator equipped, maintenance satellite controlled from the ground. In such a system, communication transmission links are a governing parameter. These are known factors. Yet the Brookhaven servo manipulator is to my knowledge the only powered master-slave device where communications are used as a major optimizing parameter. What can we learn from this? Let us consider a figure of merit using the following parameters: keep total available bandwidth constant and find what sensors to apportion to it for optimum dexterity. Let me illustrate: a present-day high-resolution TV system takes about 1×10^7 Hz bandwidth. The force feedback on the Brookhaven servo manipulator, without any fancy bandwidth compression, takes 5×10^3 Hz. So we can run a force feedback back to the operator for 1000 arms on the same bandwidth as one TV system. Now, we can see the fallacy of the argument that a power master-slave manipulator is too complicated. What is the point of saving kHz bandwidth when MHz are required anyway? Furthermore, one can hope to get a force-reflecting system to do some blind work, which we all know cannot be done without it.

The foregoing also throws a new light on Ray Goertz's work on head-controlled TV motions. It is obvious that bandwidth-wise we can use five or more servo motions much more economically than an additional TV camera. Particularly striking is the fact that in one-g gravitational fields most of the energy supplied to a master-slave manipulator is used to fight gravity. This leads to difficult energy-transport and actuator-interface problems. These problems are much eased in low- or zero-gravitational fields, which immediately leads one to think of power master-slave manipulators in space exploration.

I would like to skirt the issue of men in space vs computer in space. Actually, I am not sure that we can do reasonable space exploration without either of these systems. I am, however, sure that neither system can do too well without appropriate manipulators. This is certainly true of computer systems. However, I had best leave details of computer-manipulator systems to people working in that field, and talk about the man-manipulator systems with which I have some experience. To explore space, the moon and planets, man must be able to perform work there. Somehow we have assumed that the way to do this is to put man in a space suit. To my knowledge, and I might be wrong, this assumption has never really been examined. I would like to suggest that we do examine this since I suspect that it is not quite valid.

Existing servo manipulators, clumsy as they are (including the one described here), are of about equal dexterity to a man in a space suit under zero-gravity conditions. Endurance-wise they are superior. I know that considerably more money has gone into space-suit development than into the development of servo manipulators. I also know that people in the servo-manipulator field have a pretty shrewd idea how to build space manipulators with drastically improved dexterity and lower system weights than those of the average astronaut in a space suit. It is time we took advantage of this knowledge.

Much has been written about the various orbital repair, refurbish, and assembly missions. In the light of recent experience at Brookhaven, the majority of these studies have grossly overestimated the bandwidth requirements as well as the weight and size requirements associated with power master-slave manipulators in orbit. These estimates are high not just by 10 percent or so but by orders of magnitude, which puts the problem in an entirely different light. It means that servo manipulators are realistic and it certainly looks even less realistic to use unilateral manipulators for these applications.

Exploring for a moment a more dramatic field, a considerable saving in payload requirements could be effected by soft landing on a planet a compact manipulator module controlled from a planet-orbiting manned capsule. This technique has not been discussed much, mainly because estimates of manipulator module weight have been too high. With recent experience of the Boookhaven manipulator more realistic estimates are possible. This occurred to me when Apollo 8 was flying around the moon and the module was sitting on the ground because mostly, as I gather, life support systems were not checked out. Of course, this is hindsight, but we could have put a nice space manipulator in the LM, let it land, explore the moon by remote control, gather up whatever we wanted, and bring it back for earth laboratory examination. If something had failed to function we would have lost a manipulator system and an LM; but we would not have lost any astronauts. If the test had been successful, we would have had a better test of the LM than will result from next week's Apollo 9 in earch orbit. I don't know why this hasn't been thought of. It certainly deserves consideration when we explore Mars, Venus, or other planets. There is an enormous payload reduction when we can send, let's say, a group of men into orbit around a planet, while a small manipulator module lands, explores, picks up whatever is needed, and then brings it back to earth for examination. This is an intermediate stage between the automated laboratory and manned landing. The advantages

are that man-directed exploration and selection of specimens can occur during a considerable portion of each orbit. If the system includes capability to reorbit, rendezvous, and dock a few pounds of payload with a manned capsule, quite good samples might become available for earth laboratory examination. I understand that it might be possible to stretch the Saturn V booster capability to do this. All I want to say is that the manipulator system required can be built today.

Now let us talk about technology utilization involving simpler applications. I feel confident that with today's technology we can reduce cost and improve dexterity enormously. Let us postulate a telemanipulating system with DQ approaching 100, purchasable at a cost comparable to a modestly complex machine tool, and we have a way to reduce any dirty, dusty, toxic, smelly or otherwise dangerous and unpleasant job to a pleasant and highly skilled occupation.

I believe we cannot solve our present social problems until every person working for a living truly respects his job. As an illustration of what I have in mind, let us mention coal mining, which is the most dangerous occupation in this country. In 66 of the last 68 years we have had at least one major disaster. Those miners spared by disasters are threatened by lung disease which, according to the lowest estimates, disables over 10 percent of coal mine workers. The actual work conditions can only be appreciated by somebody who has visited a mine. We know that such safety and health conditions would never be tolerated in the nuclear or space fields. Coal mining is nearly as automated as it can be. There is no reason why any human being should ever descend again into a coal mine. The state of the art is coming close to the point where servo manipulators can take over the remaining manual jobs in mines. Incidentally, this has the advantage that no jobs are eliminated — they are just made safe and clean. However, to do this the major problems to be solved are social and economical, not technical.

CHAIRMAN JOHNSEN: I just want to point out that Bill Allen over at Ames Laboratory has coined a name which I think is very good — "expendable explorer."

MR. FLATAU: A very good word, but I would suggest that we do not have a good explorer unless it includes some manipulator module along the lines I was talking about.

QUESTION: Mr. Flatau, your work seems so outstanding, it evokes a couple of questions. What are your basic objectives in developing master-slave manipulation? And what makes you think force feedback is so valuable?

MR. FLATAU: The objective is to furnish general-purpose remote handling for high-energy particle accelerators. As regards the value of force feedback, the hardware seems well suited for testing these parameters. In our system force feedback can be switched off, so that we have a proportional servo without force feedback. Even without the benefit of numerical results, initial tests indicate that a remarkable deterioration in dexterity occurs. We could easily rig up seven switch controls and operate the slave with open-loop rate control. In the latter version the DQ might be down about two orders of magnitude over the force reflecting version.

QUESTION: How do you relate this to the objectives now in your program?

MR. FLATAU: Let me put it this way. Due to operational demands in an accelerator, the time allotted to maintenance is reduced to an absolute minimum. On the other hand the complexity of an accelerator requires the utmost in general-purpose remote-handling ability. Both of these requirements point to the most dexterious remote-handling system possible. This requires use of servo master-slave manipulators. At CERN, an accelerator laboratory near Geneva, Switzerland, commercial switch-controlled power manipulators have been tried. The results have been disappointing, probably because of the kind of manipulator used. The developments under discussion are intended to rectify these shortcomings as far as the Brookhaven program is concerned.

QUESTION: Why are you developing along this particular line instead of just building a machine like Ray Goertz has developed, an electric mechanical manipulator?

MR. FLATAU: Ray Goertz's was too big, so I had to make a smaller one. I would have bought Ray Goertz's had I been able to see a way of fitting it in.

QUESTION: Why didn't you build one smaller than Mr. Goertz's?

MR. FLATAU: I did, but one can't scale these devices very well. The essential difference is that Mr. Goertz put all his actuators in the shoulder and brought the motions

into the arms via cable drives. I think Mr. Goertz will agree that if one does this, one can't get overall size down as small as I have been able to. One can achieve a smaller wrist diameter, but the overall size is larger. The way to reduce overall size drastically is to put all the actuators in the arms.

QUESTION: What is the need for the elbow-wrist action here? I think, for this kind of thing, the crane type of electro-linear motion would be adequate.

MR. FLATAU: Not necessarily. Added to the slave, there will be what we call an indexing motion, which is an open-loop, three-degrees of freedom motion, one of them along the tunnel, one across the tunnel, and certain ones up and down. This is just to position the manipulator wherever you want it. However, it positions the manipulator only in the desired location. For our purposes, therefore, this kind of open loop system is just not adequate; I contend it won't do the job.

COMMENT: You have to have a position servo.

MR. FLATAU: I do not believe that a position servo is as beneficial to manipulator dexterity as one might think. Incidentally, in this connection I would like to emphasize that force transducers are not required to achieve force reflection or feel. This can be done by driving both master and slave, albeit in opposite directions, from the same position error (as it is done in the Argonne servo manipulators). The reason I went to force transducers is that it was the only way I could find to reduce reflected motor and gear-train friction and inertia forces, and that is very important.

QUESTION: Your sensors are downstream?

MR. FLATAU: Yes, as close to the output as possible. The only limitation I have, is bringing the gain up high enough without getting into servo instabilities. But I have an overall gain of 25 to 30, which is respectable.

QUESTION: I am interested in your speculation about space. Do you think the permanent magnet dc motor is about as good as a power actuator for this application as you can get?

MR. FLATAU: The motors we are using are basically adaptable to running in a vacuum provided one makes provisions

to dissipate the heat produced. I hesitate to lay down a blanket prescription without considering more detailed design objectives.

CHAIRMAN JOHNSEN: I would like to make a change in the program to accommodate a gentleman who will have to leave early this afternoon. We will hear from Dr. Thomas Kane, who has been doing some work which is related in a way to the whole system of teleoperators. Dr. Kane.

DR. KANE: Thank you. I didn't know until 8:30 this morning that I was going to be on the program, so I have no slides, films, or other aids with me. However, in May there will be a conference at the University of Santa Clara, called the Aerospace Mechanisms Conference, which may be of interest to some of you.

My interest in space maneuvering is purely academic. I teach mechanics and advanced dynamics, and many of you know that in textbooks on mechanics there is frequently a reference to the cat and its ability to turn itself over when falling in space. This is usually tied to a discussion of angular momentum and a description which involves pulling legs in, twisting, and pushing legs out again, perhaps whirling the tail. All this seemed fairly unconvincing to me. So I started looking for an explanation of this phenomenon, and after considerable time and inspection of films, etc., succeeded in what I regard as a fairly good explanation of this phenomenon. I then began to realize that, potentially, this was a field to explore for use in the space program. Of course, an astronaut in extravehicular or even intravehicular activity has considerable need to reorient himself, and if body movements can be used for this purpose, it would certainly be the simplest system one could hope to use.

Obviously, one cannot use limb movements to produce translation, but if one could combine a system which has translation capability with limb movement to provide rotation, this could, in principle, be a very effective scheme for accomplishing all the maneuvering that is really necessary. The thought is even clearer if one considers that a human being does in fact possess the capability to use his body effectively to achieve controlled motions as a whole. So we began to explore this from a purely theoretical point of view. We simply modeled the human body as an appropriate number of subsystems and then wrote dynamic equations and tried to solve them. In principle, this should make it possible for man to reorient himself in almost any desired fashion.

We have tried this out experimentally with a man on a trampoline. This is a very good experiment in that it really duplicates the free fall condition of space completely because, once the man is off the mat, he is falling freely. Still, a man has considerable ability to affect his motion by the way in which he pushes off from the trampoline, and the experiment must necessarily be of very short duration. However, by giving commands to a man in midair, we have been able to eliminate push-off effects. If you tell the subject whether turns are to be to the right or left after he gets into midair, he obviously cannot have predetermined his motion by the way he leaves the mat. We are convinced on the basis of these experiments that it is possible to execute such maneuvers very effectively. We have also tried them out on an air table briefly. This is a questionable technique because it is not truly three-dimensional, but it suggests that we are doing the right sort of thing. Most recently the Martin Company has constructed a simulator on which one can do truly three-dimensional maneuvers, and we have attempted our maneuvers there and seem to get qualitative agreement between analysis and the real world.

Our next step will be to try our maneuvers in space, or perhaps first in zero-g flights in aircraft. Eventually, we would like to combine body motions with a very simple arrangement of thrusters so that we can use the body to do all the controlling, with the thrust serving only as a propulsion device.

Thank you.

CHAIRMAN JOHNSEN: Is there a possibility that this work then could be used for controlling unmanned manipulator vehicles?

DR. KANE, Stanford University: It seems to me there is no reason not to think along those lines. The dynamics are the same. The human provides, in the kind of thing we are talking about, the feedback loop. He is in a sense the actuator as well. But there is no reason why he can't replace these functions mechanically. Exactly the same concepts could be used, and if you plan to have the manipulator doing work outside the capsule, you need a means of reorienting it. Thus, it will be the same problem for the device as for the man. There is no reason not to use the same solution for the same problem.

QUESTION: Can you say where this work is published, and is there one central place?

DR. KANE: We have written several reports which can be made available in a limited number of copies. They are called "Reports of the Department of Applied Mechanics." Requests for copies should be sent to the Department of Applied Mechanics, Stanford University, Stanford, California 94305.

There have been various technical papers published by way of general literature. One appeared in the "Journal of Applied Mechanics" about two years ago. A forthcoming paper in the "International Journal of Solids and Structures" will contain a detailed description of the cat-overturning maneuver.

CHAIRMAN JOHNSEN: Are there any further questions or comments?

QUESTION: There is a lot of work that Carl Smith of the University of Wisconsin has done on the locomotion of walking and the human body. Are you familiar with his work?

DR. KANE: To some extent. The problems, however, are fundamentally quite different. When you remove the gravitational field, you also remove all the reactive forces you get from the ground, and the dynamics of the situation change drastically. Most of the work on walking and skiing, as well as in other athletics, is in many ways quasi-static. The important forces which come into play are really forces of reaction to gravitation. So the dynamics per se are of secondary importance.

CHAIRMAN JOHNSEN: Thank you very much, Dr. Kane. I would like now to go on to the next topic —a talk by Dr. Bliss of the Stanford Research Institute on tactile systems.

DR. JAMES BLISS: Remote manipulation is a new field to me. My research over the last few years has been on tactile display, and I'd like to describe that work in the light of the intended applications for this research, and then discuss whether or not these techniques have promising applicability to remote manipulators.

Our laboratory has been working on tactile displays for a number of years under NASA, Air Force, and HEW sponsorship. This work has involved the development of individual tactile stimulators and of arrays of such stimulators. We have also studied how arrays of tactile stimulators can be controlled. This has involved many psychophysical experiments on the stimulus parameters for tactile sensations, on information

processing models for the tactile channel, and on some application areas using these tactile displays. Rather than trying to summarize all of this work, I will only talk about the parts that I think would be of interest here. We have developed several types of tactile stimulators—airjet, piezoelectric bimorphs, electromechanical, and electrical. Probably the most interesting of these in terms of teleoperators is either the airjet or the piezoelectric bimorph. For those who aren't familiar with this equipment, it consists of two layers of lead zirconate which may be about an inch and a quarter long by 40 mils by 20 mils, in the form of a sandwich. The two layers of lead zirconate are oppositely polarized so that on application of voltage across them, one will expand and the other contract, causing the unit to bend. The typical mode of operation we use for tactile stimulation is to cantilever one end. We let the free end vibrate when we put an electrical signal near resonance on the unit. We mount a small pin on the free end and let this pin vibrate up through a hole in a sensing plate which can be placed on the skin.

We built an array of 144 tactile stimulators for the stimulation of a single fingertip. It covers an area of about 1-1/8 by 1/2 inches, and represents a matrix that is 24 stimulator rows high and 6 columns wide. The top plate is curved to fit the finger. This unit was developed as a display for a reading aid for the blind (figs. 26 and 27).

We also built an optical pickup that images about a letter space from a printed page onto an array of phototransistors. These phototransistors then give on or off signals to the array of tactile stimulators. As a blind person moves the probe containing the phototransistors across the printed page, he feels the tactile copy on the stimulators of the optical image. There is also an array of light bulbs that are one-to-one with the array of tactile stimulators. We have completed several of these systems and have taught blind people to read in the range of 20 to 50 words per minute.

We are very interested in the possibility of using these stimulator arrays for feedback of touch information in teleoperators. Instead of an optical pickup, we would couple the stimulators to an array of force transducers to give a manipulator the tactile feel that one might get if he grabs something. The system would primarily transmit the distribution of forces, rather than the gross force itself.

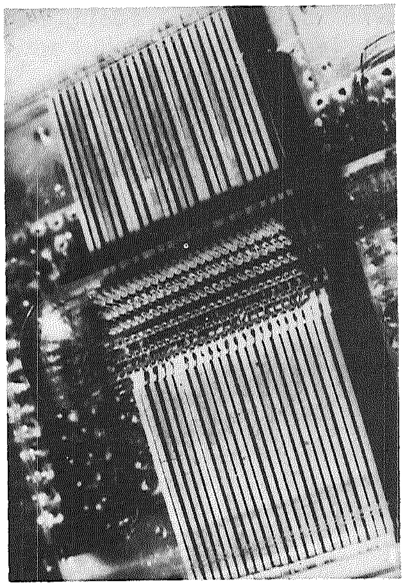


FIGURE 26

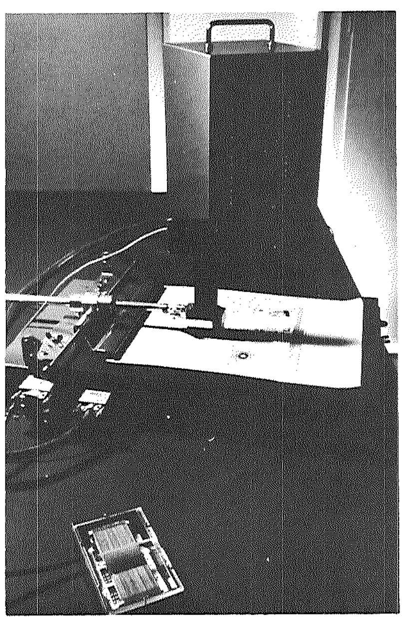


FIGURE 27

We have also been working on a tactile TV system. It has very crude resolution, of course, but we built it using the same techniques as for the reading aid. Instead of using an optical system that images a portion of the printed page, we put camera optics on the front of the device and imaged about a 30-degree field of view. The electronics are contained in a portable unit and the system is analogous to a 12-line TV system.

These are some of the techniques that we are working on in tactile displays. In addition, other things are going on in our group that might be of interest. These have to do with vision. We are working on techniques for measuring the direction of gaze, that is, where someone is looking in two dimensions; and techniques for measuring the distance that the lens in the eye is focused. We can measure the direction of gaze in X and Y with about five-minute accuracy. This technique distinguishes between translations and rotations of the eye.

In order to tell where the person is looking so we can put the high resolution area of a TV system in his fovea, you have to distinguish between rotations and translations of the eye. This is done by scanning the first and fourth Purkinje images — these are images that are due to reflections from the cornea and the back side of the lens. Because of the difference in curvature between the surfaces forming the first and the fourth Purkinje images, these two move differentially with respect to rotation of the eye and they move together with respect to translation of the eye. Therefore, if you can measure the distance between these two images, you can measure rotation independent of translation. You need to do this in order to get an accuracy that is much better than a half a degree or so. This development, which is NASA-sponsored, might be of interest in some of these dual channel TV systems for teleoperators.

QUESTION: What is the sensor used to read the print?

DR. BLISS: We are using an integrated array of phototransistors. This is an array that was built in Stanford Electronics Laboratories and consists of 144 phototransistors on a single silicon chip in a 6 by 24 matrix. Each phototransistor is 5 by 10 mils.

MR. CHATTEN, Control Data Corporation: Would you comment on the relationship between this system of tactile display and Braille. I think you said 20 words a minute was achieved with this. How does that compare with Braille?

DR. BLISS: Dr. Murphy can correct me on this, but I think 100 words per minute is a common rate of reading Braille. Braille involves a complex translation that would require character recognition in any system such as we have described, and hence, a more expensive system. In addition, the 100 words per minute rate is for contracted Braille -- more of a shorthand. It is not a leter-for-symbol translation. The idea is to make our device simple enough for a person to read any document as it stands, no matter what type font or format, without having to evoke the complexities of character recognition. Character recognition may be relatively simple if you control the print, but it is very complicated if you want to be able to read.

DR. MURPHY, Veterans Administration: May I break in on this?

CHAIRMAN JOHNSEN: Dr. Murphy.

DR. MURPHY: Regarding Braille speed, I have a little card that our office has prepared on a British study in which they interviewed 1464 people. Of these, 327 felt sufficiently confident of being able to read contracted Braille, even to take the test. Of those tested, approximately 72 percent read less than a hundred words per minute. On the other hand, there were a few, about two percent, who read at over 200 words per minute. So this is an extremely variable skill. I would argue it is important to read a limited amount of Braille at a very slow speed so you can make your own labels for medicine bottles, read the labels on the Talking Book records, use your own card file system for addresses and telephone numbers, and so forth. It turned out that 41 percent of the people actually tested (or about 9 percent of the total interviewed) read some 50 words a minute or less. These are people who probably have miscellaneous uses but never become highly skilled. Most of the people who are really good are fast readers brought up since childhood in a school for the blind where they had constant drill in high-speed Braille reading and lots of incentive to use it.

MR. NEVINS, M.I.T.: One question bothers me; we are talking about pattern recognition techniques, but the techniques that you are using don't seem even to approach the speed of Braille, at least in the numbers you quoted. Possibly the pattern you are presenting is more complex to the individual than Braille.

DR. BLISS: It certainly is. Braille is a six-dot code and I am presenting 144 dots, which is quite a bit more complex. We have done some visual reading studies, by the way, which indicate that with this size field of view, visual reading isn't much different from what we are getting tactually. We think that the way to increase the reading rate is to increase the field of view, and we are experimenting with techniques for doing this. Further, we have only had a device with adequate resolution for testing for a few months now, and while our subject has had practice over a number of years on lesser devices, there is no indication what the rate will be, given a year or two of practice. The best rates we are getting now are something like 50 words a minute.

MR. NEVINS: How do you increase the field of view?

DR. BLISS: Go to more fingers.

MR. CHATTEN: Does the current tactile stimulator exhaust the resolving power of the finger.

DR. BLISS: I think the current one with 144 points does, at least with the amount of training that our subject has had. It is a very curious phenomenon, but even simple resolving tests on the skin, like a two-point resolution test, seem to improve with practice. We have done legibility tests in which we tried to stimulate closer together and further apart, and at least these indicate that we are right at the edge of resolution.

QUESTION: Disregarding development costs, within how many years would you say we are of having a finger-mounted reading device for a blind person?

DR. BLISS: We have designed an improved battery-powered version of the device, more portable, and compact. Within the next year, we expect to have ten prototype units available for more extensive manufacture, with only minor modification.

QUESTION: The type you showed there involved the printing matter having to be below a fixed viewer. Is there a possibility of having a tactile device on a blind person's finger so they could just scan across the page with their finger?

DR. BLISS: We haven't worked on that approach yet because we felt that a resolution of at least 144 points

would be needed for adequate reading and we haven't been able to achieve this without sacrificing maneuverability of the probe. I think Dr. Murphy will probably talk about another system that does use this approach.

DR. MURPHY: Nearing completion in the next month or so are ten Visotactors, which are being built by Mauch Laboratories for us, and 30 Visotoners, which correspondingly put out tone patterns related to the shapes of the letters. We are in the process of setting up some sort of clinical application study of these devices. During the last couple years, I think we had six Visotoners and three Visotactors which operated on a very limited basis. We also have some training methods that were developed and tested by the Battelle Memorial Institute, and initial screening techniques that were evolved by the Hadley School for the Blind to try to select suitable candidates for the Visotoner device. These are merely steps towards more sophisticated recognition reading machines, the Mauch Cognodictors, of which three are being built in this fiscal year or this coming summer.

CHAIRMAN JOHNSEN: Thank you very much, Dr. Bliss, for coming.

Mr. Wirta, how about telling us what you have been doing in the way of electromyography (EMG)?

MR. ROY W. WIRTA, Moss Rehabilitation Hospital: May I address this part of the discussion to a very narrow aspect of aids to the handicapped? As the program indicates, Dr. Murphy is going to follow me and he will give us a broad view, so it resembles the curve over here where I will be looking mainly at the foveal aspects. What I would like to do is report our progress and status on EMG control, the myoelectric control of external power. I would like to begin by telling you the objective of our research program.

Now, for those who might need a little bit of introduction, myoelectric means muscle electricity. Any time a muscle is contracted there is a small voltage generated which can be found in its surroundings, whether it is detected near the muscle site itself or whether it is sensed on the surface of the skin overlying the muscle tissue.

In our particular approach we have used surface electrodes. There are several reasons for this. First, we don't have to penetrate the skin. Second, if we were to use a needle, I think we would be looking at the small domain

within a muscle close to a muscle fiber in size and not really know what the total muscle might be saying. There has been a lot of work over the past decade in areas such as control of terminal devices, and more recently, powered elbows. These devices in general are a one-for-one type of device, that is, looking at one muscle site for control of one direction of motion.

All of you who are acquainted with some of the problems in remote handling and manipulation recognize immediately that controlling each motor in a multiaxes manipulator, with its individual switch, makes it very awkward to try to control several motions at one time and to achieve movements in any coordinated fashion. That is, that we can use a mechanical coupling between man and machine to introduce coordinated motions so as to increase the speed and accuracy of these operations. If we look at the human organism more closely, we note that there is another means of communication between man and machine. Therefore, I'd like to address this discussion to an electrical means, that is, a myoelectric control. Conventional prostheses are body powered and very limited. A person who is an above-elbow, bilateral amputee, for example, is fairly helpless in many aspects of daily living requirements. So we addressed ourselves to that severely handicapped individual. Additionally, rather than looking at a one-for-one control, we tried to get a physiologic type of motion into the external device. Further, since there have been numerous developments in the area of myoelectric control of terminal devices, we did not address ourselves to the terminal device control but rather to its positioning and orientation in space, so that the amputee can do something with it.

All of us in the process of growing up learned a number of motor skills, and we perform them, giving hardly any thought to the process. Rather we think function: "We want to put our hand over there; we want to do that task." You see, we need only to think that we want to accomplish an act rather than to think out the procedure motion by motion. So, in answer to the question of a technical approach, we said to ourselves, "All right, let us harness nature's own organization in control." To solve the problem, we used a computer program called the Multinorm, which is a multivariate-discriminant-analysis technique. With this tool we could investigate a number of variables which occur simultaneously and make sense out of them for the purpose of controlling specific functions. In other words, we said, "Let us look at the muscles in the back, in the chest, and in the shoulder, and

see how important combinations of these muscle sites are in discriminating or distinguishing one motion from another." Indeed, we determined weighting coefficients for each of 10 muscle sites for each combination of movements.

We implemented these weighting coefficients into a control circuit utilizing a simple resistor network as our discriminate mask. We were pleased to find that this mask, designed on the basis of one normal person, has allowed one normal person and three amputees to operate the prosthetic arm with almost no training. They simply activate muscles in the accustomed manner of what they want to do and the arm does it.

I'd like to show two motion pictures. One shows a bilateral amputee operating our experimental arm. This experimental arm is far from something which is ready to wear. We built a control and we deliberately unminiaturized it into a fairly large console so we could have enough peripheral space to include dials, knobs, and switches to vary circuit parameters. We can vary the gain of each myoelectric channel. We can adjust thresholds within the pattern-recognition network. We can vary the forward gains within the arm mechanism as well as two feedback gains, one being torque and the other velocity, as well as changing time constants. All this latitude was included so that we could solve the problem by an experimental approach, dealing with the man-machine system. While we are far from having completed our work, I think we now have the capability.

If we could have the first film, I can narrate it while we are looking at it. These are engineering documentation films taken the first time each of these specific subjects operated the equipment. Shown on the screen is a bilateral amputee who, prior to this, had not controlled the arm. We had gone through a preliminary checkout procedure, tuning up the circuitry so that it would function for him one motion at a time, and in the process got it to the point where the controls worked reasonably well. During that time we took these scenes showing how we attach the arm and execute the motions. The electrodes, which you see, are ten in number, one on the chest, three on the shoulder, and six on the back.

The next film will identify these muscle sites and you will see in a little more detail how we applied the electrodes. Notice that the amputee is being coached off camera to perform the motions bilaterally, that is, to reinforce the recall of the kinetic formula within his organization of motor skills in order to make this arm work. Later on in the

sequence of shots you will see that he doesn't use his left arm any more. These scenes were taken when he tried to operate the device for the first time. He has since become proficient.

The arm mechanism itself, as you see, is not wearable. We built it fairly large; we did not spend a lot of time in mechanical refinements because we felt unless we could show the practicability of the control, there was little point in spending a lot of time on the arm. Having achieved this degree of success, we may devote our efforts to refining the mechanism, making it cosmetically acceptable, light, and rugged; improving the harnessing technique (this one is particularly makeshift); and miniaturizing the electronic controls.

Next, you see the subject being coached to do pronation and supination. All the signals for that pronation and supination function are resident some place in those fixator muscles which act in synergy. These are fixator muscles in the back and the chest which produce the control signals for those movements.

QUESTION: Which electrode is giving him pronation?

MR. WIRTA: There are several of them. There are several sites which serve at one time. It isn't just one muscle; it is a group of muscles which are responsible for distinguishing that motion from some other motion. We do not look just at any one site to make the decision. It comes on the basis of looking at ten sites (ten electrodes) at one time.

In these scenes, we are operating from a 12-volt source to the electric motors, which are simply slot-car motors. On subsequent tests, we increased the voltage to about 18 volts, and the arm was very snappy. As a matter of fact, if we go to 24 volts it is a little more than can be handled reliably. It gets into body dynamics and you face the problem of modulating the signals being monitored. This happens to be another control parameter variable which we have built into the test bed to enable us to define the system requirements for an amputee operating an arm such as this.

QUESTION: Is this fatiguing for him?

MR. WIRTA: No, he is using extremely small levels of effort. The next film will show you a little bit about the sensitivity factor. The data we acquired on the normal sub-

ject was in the order of five percent of maximal effort. This system was designed to handle ten pounds, but we have not applied ten pounds yet; we did apply a load of five pounds, which the subject handled with considerable ease. His comment was, "Gee, I have to try a little harder," precisely what we wanted him to do. There are, as I indicated, torque feedbacks, and the transducers are strain gauges mounted on beams located on the output end of the gear trains. We are trying to determine appropriate types of torque feedbacks.

This bilateral, above-elbow amputee, a Vietnam casualty, was a very useful subject for us. He helped us in receiving nationwide publicity on February 10th when we had a publicity release, TV and national news coverage. For those of you who would like to get a layman's viewpoint of what's going on, you'll find it covered in the February 24th issue of NEWSWEEK, in the Medicine Section.

While we are changing reels I would like to show you this slide (fig. 28). You see the amputee at an easel. He is writing. This is a picture taken during the time the TV pictures were being filmed. We put a felt pen into the terminal device, and he went to the easel and printed very legibly. The first words that he printed were: "Hello there," and right here in this particular shot he is writing "Hello, Pat." Pat's his wife, who has been extremely helpful, doing things for him.

QUESTION: How long was he an amputee?

MR. WIRTA: I am not sure when he returned from Vietnam, but I think it was about eight months ago. His stump is pretty well healed up. It no longer causes pain, although the scar tissue at times gets rather sensitive.

QUESTION: To what extent do you have to adjust the gains at the various muscle sites from individual to individual?

MR. WIRTA: This has not yet been evolved into a scientific technique, but it is not very extensive. We are looking for ways in which we can study this 60-dimension problem. Note that we have ten sites and drive three motors in two directions, hence, a multidimensional problem. Right now Don Taylor, who also appears on the still picture, has all this in his head in a way that he approaches by trial and error. He knows pretty much what the latitude of variation is from one person to another by observing the input myoelectric

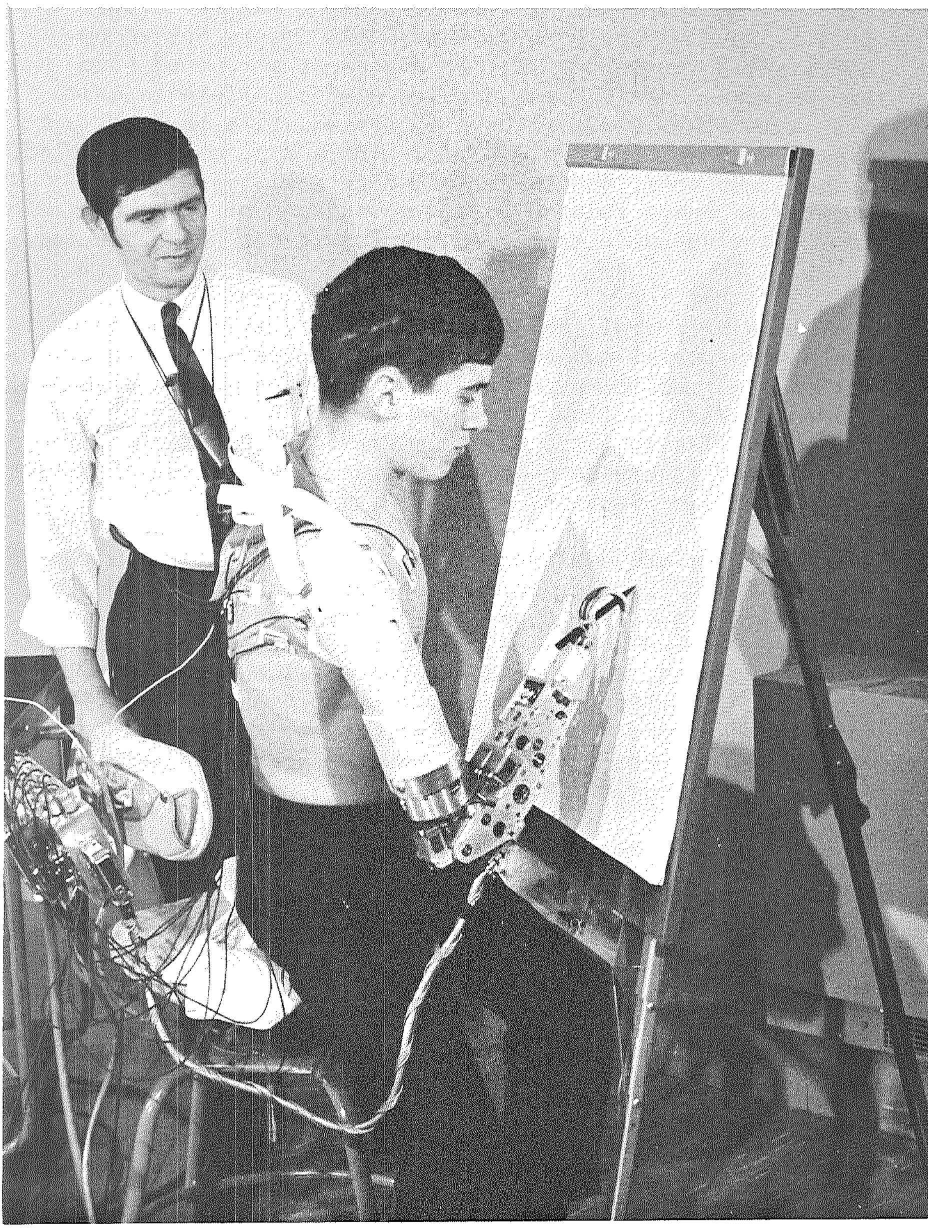


FIGURE 28

signals on an oscilloscope. We have done a considerable amount of analysis of myoelectric signals over the past three or four years and know that there is a tremendous amount of variability in signal amplitude, but the pattern among muscle sites is quite consistent.

The tool we used on this was a statistical program, looking for central tendencies. Hence, the mask which distinguishes one motion from another is fairly broad in its latitude, yet when we adjust the gains on the myoelectric channels, to tune them to the particular individual, this in turn effects changes in some of the weightings in the mask. Then we have to go back and readjust the thresholds slightly before the signal passes through the mask to turn on a specific motor in a given direction. Incidentally, we also have proportional control, so we not only sense a specific motion but also its extent.

CHAIRMAN JOHNSEN: What is the possibility of miniaturizing the span of recognition on this thing?

MR. WIRTA: I think the possibilities are tremendous, because with modern technology it's easy to pick out components which are so small you can't work with them except with a pair of tweezers and glasses. We didn't want this kind of equipment to work with experimentally, so the pattern recognition network was put on a standard card, spreading the resistors out so we could go change them if we needed to. The pattern recognition network itself can be made very small ultimately and the accompanying electronics can be miniaturized. For example, it might be put into a small package like a paperback book.

We have developed and constructed some surface electrodes at our own facility. They contain a built-in differential amplifier with about a hundred gain right at the electrode site before the signal enters the cable and proceeds into the electronics. I would like to mention that during recent tests, a man was arc welding about 20 feet away. There was no interference in our equipment, no spurious motions, no inadvertent movements by the artificial arm. This is a technique we use for attaching the electrodes. We have a double-sided sticky tape with two holes perforated in the tape. We put electrode jelly into the holes to make the electrical connection from the skin to the electrode, and then apply the electrode to the skin.

Toward ultimate objectives, some exploratory work has been done in eliminating the need to attach electrodes to the skin. We feel confident that electrodes can be installed in the socket or in the harnessing and be a permanent part of the device, so that the amputee needs only to stick his stump into it and the electrodes are in place. For our research purposes, however, we have stayed with this particular technique to eliminate interference from artifactual motion.

You might wonder why did we suspend this man's hand on that Ace bandage. We discovered that it took an infinitesimal amount of movement on his part to activate the prosthetic arm; it would have made a rather poor motion picture to show the correlation between his movements and those of the pedestal-mounted arm. The bandage counters the gravity effects so that he could move his arm up and down and sideways through a considerable range in order to show the relationship between what he is doing and what the arm is doing. At the time, we did not have the pronation-supination function working; we were simply interested in documenting the first two motions which we had activated.

Between the beginning of the film and the latter half, which covers several months, we demonstrated the utilization of the pronation and supination function. You note the subject is not looking at the equipment. At this stage he said, "I don't like to look at the equipment because I tend to follow the arm." This device is operating on an open loop. We have not yet approached the problem of how to display position and force information back to the subject. I am encouraged by techniques discussed by Dr. Bliss; perhaps through some such means of displaying position reliably to the patient, we will be able to provide position feedback. Recently we said to the bilateral amputee: "Shut your eyes and see if you can position your arm some in specific planes." His performance was not too bad. He was picking up cues of pressures and torques on his stump and he had some notion of where the arm was, but certainly he had no notion of what the position of the hand was — whether it was palm up or palm down. Does this help project some of the notions of myoelectric control into possible manipulator control?

QUESTION: Yes, why does it take so long to follow?

MR. WIRTA: I wish I could explain that to you adequately. I, as a mechanical engineer, can't put it in the terms which Don Taylor the electronics engineer does, but it has to do with the gains between the EMG signals and the gains in

the forward loop of the arm mechanism itself.

MR. ALLEN: Mr. Wirta, there is actually a lag in the EMG signal that accounts for a portion of the delay. In other words, the myoelectric signal appears after the muscle has contracted and continues for a very short period after the muscle has relaxed.

MR. WIRTA: I may be looking at this a little differently. The muscle starts to contract before actual motion of the limb occurs. In this case, the integrating circuit was operating with about a hundred milliseconds time a constant to smooth the signal. There is about a tenth of a second lag just in that alone. Then, there are other lags originating in the torque feedback and the velocity stabilization of the servo arm. So, lags from all of these sources in the system conspire to produce a delay. When the amputee operates this, he is not aware of any particular lag because he has not yet been faced with the task of doing something on an emergency basis but, rather, pre-thinking what he is going to do.

QUESTION: I have noticed that the gentleman who is running the arm is keeping his other arm in a fairly static position. How much false information does he get if he does move the other arm?

MR. WIRTA: We know the gravity vector relative to posture is important, particularly when the subject alters his posture from the position at which the design data were obtained. However, how much posture change can be tolerated is something we are not ready to define. We know that we have reasonable latitudes, but we don't know their extent. This is important, because when the amputee starts doing some functional tasks, like tying his shoe laces, these certainly introduce the need to determine the effects induced by altering posture or position of the contralateral limb.

CHAIRMAN JOHNSEN: I would like to say that Dr. Kelly and Dr. Wargo have been working on what they call MAP, which is Muscle Application Potential. They have studied the time lag which is caused by it and how to cope with it. Maybe when Dr. Wargo talks to us he can cover that subject, or do you want to cover it now?

MR. WIRTA: How many cycles per second did you achieve, roughly, about three cycles per second or so?

DR. WARGO, Dunlap and Associates: I can't remember, but it was infinitely higher with my hands. That appears in NASA's publication.

CHAIRMAN JOHNSEN: Let's have about three questions and then we will go on.

QUESTION: Do I read you right when you imply that the electrode problem has basically been solved and that the question of implanted electrodes is a blind alley now?

MR. WIRTA: No. We simply have chosen surface electrodes for our particular purposes. There is a lot of excellent work going on in the area of implanted electrodes for other purposes.

QUESTION: What caused the false motions of the arm?

MR. WIRTA: I think it's simply reporting upon the muscular activity of the individual who is operating it. Perhaps they are not so much false motions as manifestations of muscular activity when he is thinking about starting to move his arm. One of the first reactions by the subject in the last film was to stop looking at the prosthesis. On that occasion, he brought his arm up and did something and the response seemed contrary to what he thought he did. He said, "Ah, I caught that machine doing what I didn't do." Then he stopped to think for a moment and he said "Damn, that's exactly what I did do. It tells the truth. Now I know why it happened the way it did."

COMMENT: But this occurred even when he wasn't looking at the arm.

MR. WIRTA: There is no position correlation between the man and the machine in this case. This is an open loop with no position feedback. Hence, should a motion be identified which is not large enough to be manifest in the limb motion, it appears as though an inadvertent motion occurs.

MR. JOHN SCHWARTZ, Denver Research Institute: What was your comment about proportionals? I missed a little bit.

MR. WIRTA: In our case we do control the power to the motors. First, we decide what is to be done; then right after that we decide on the extent. The signals emerging from the decision network come to a summation point and then we estimate how much the signals exceed the thresholds.

This drives the motors at different speeds corresponding with the amplitude of the myoelectric activity detected at the muscle sites.

MR. SCHWARTZ: You use an amplitude for your proportional discriminate — is that what you said?

MR. WIRTA: Yes. It is the energy content which we use from the signal.

CHAIRMAN JOHNSEN: Dr. Murphy, you've got a hard act to follow.

DR. EUGENE MURPHY, Veterans Administration: I am concerned with research on artificial limbs, braces, hearing aids, aids to the blind, and just about everything between wigs and orthopedic shoes. Naturally, I don't know much about this rather diffuse field. There has been an active research program in prosthetics since World War II, in this country, and of course there were programs in World War I in Germany (leading to the famous book "Ersatzglieder und Arbeits-hilfen," published fifty years ago this year), Belgium, England, and elsewhere. This time, however, we have been fortunate in keeping the program going continuously instead of stopping as soon as the war was over and people thought they had returned to normalcy. Thus, I think more has been accomplished this time in terms of actually reducing devices to practice.

A law, passed and approved in 1948, authorized the Veterans Administration to conduct research and development in this field of prosthetic and sensory aids, and to make the results available, so that all disabled might benefit. We tried to push this law to its ultimate in conducting research, originally with a million dollars a year. Now, we are up to about a million four hundred thousand dollars, which hardly fights inflation. Fortunately, agencies such as Social and Rehabilitation Services (SRS) and others have come into the picture with far more money than ourselves.

We have also, in the spirit of the law, used some of this research money to organize prosthetics education programs and carry on publications. This has brought the results of the research program down rather effectively to the doctors, limb makers (now the prosthetists), brace makers (now the orthotists), the therapists, and others who are concerned with knowing about the research results. Thus, members of many disciplines function together as clinical teams to treat individual patients. These teams have also been trained in the new ideas, not alone on new devices but on

biomechanical principles, methods of fitting and alignment, harnessing of artificial arms, and so on.

In 1945 the surgeons on the then Committee on Prosthetic Devices were asked to give a "bill of complaint" against the then-existing devices. They said they wanted a hand that both looked like a hand and had some degree of function and a knee for above-knee amputees that would not buckle. Note that they only thought in terms of mechanisms, or at least these were the first complaints they dared raise. It has turned out that we have not only made some progress towards these items in the Army hand and the Henschke-Mauch knee, but also towards much better principles for fitting, alignment, and so forth, and most importantly, towards getting all of these people working together in clinical teams.

Some publications give a continuing survey of this field: the magazine "Artificial Limb" published by the National Research Council, "The Inter-Clinic Information Bulletin" published by New York University for Mr. Kay's Subcommittee on Child Amputee Prosthetics Problems, and the magazine "Bulletin of Prosthetics Research" published by the Government Printing Office and prepared by the Veterans Administration. This last publication comes out semiannually, and notoriously about six months out of phase behind the ostensible dates. It is hoped that we will get back on schedule.

There are also some books in this field. The outstanding work "Human Limbs and Their Substitutes" is about to be reprinted by the Hafner Publishing Company, after being out of print for a number of years. We understand Hafner has already received 160 orders without even having any copies of the book. I have some announcements of it. Also, if anybody would like to be notified of the publication of "The Bulletin of Prosthetics Research," I have some handouts.

DR. WARGO: We ran a study on muscle action-reaction time as compared to visual and auditory reaction time, and we found something like a 30 percent reduction in reaction time with MAP as compared to hand reaction time, visual. It is a significant reduction.

MR. WIRTA: If I read you correctly, then, this technique applied to an external system control offers another means of increasing the system capability.

DR. WARGO: As a follow-up to that basic study, we developed a control or a tracking device, and we only ran one subject, which was me. I was highly trained on normal hand tracking, and received maybe a total of three hours training in the cheek muscles, tracking in one dimension — the horizontal axis. There was an increase in my frequency response. In other words, I could handle a higher frequency of the forcing function with my cheek muscles than I could with my regular tracking.

The "Atlas of Orthopedic Appliances," published by J. W. Edwards for the American Academy of Orthopedic Surgeons, the Army, and the Veterans Administration, is also a good source of information in this field, not only on devices but on other important aspects. It seems to us that the real problems of the disabled have tended to be overlooked by many of the younger bioengineers in this field.

Myoelectric or electromyographic (EMG) control has certainly attracted a lot of attention, and deservedly so, but we think it has tended to serve as bait, hopefully, to make some excellent people interested in the total problems; then possibly all concerned will take an interest in some of the other and perhaps even more worthwhile approaches to problems of the amputee.

Much of the work on EMG control has involved picking up signals from the forearm muscles and using them to control the hand. This is fine in a below-elbow amputee who has these muscles remaining. As normal persons, you can feel these muscles bulge as you move your fingers. It is quite easy to use them, as a matter of fact, to drive microswitches or equivalents with a lot less electronics. The Vaduz (Liechtenstein) hand now built in Paris was built on this concept with a rather sophisticated feedback and servo system to force the fingers and thumb to move in proportion to the bulging of the hand-clenching muscles of the forearm. The difficulty with much of this myoelectric work, however, has been that though there are numerous designs in Russia, Canada, Italy, England, and the United States for EMG-controlled hands, they are mainly for cases amputated below the elbow, who are the easiest amputees to care for by conventional means. Most of these devices have tended to use open-loop control. There has been some attempt, particularly by Bottomly, to provide a degree of feedback, but most of these designs have been relatively simple, for direct drive of the motor. To me, as a reactionary mechanical engineer, this simple,direct on-off myoelectric approach tends to give

up the control and sense of position which one can have from the Bowden conventional artificial hand or hook.

A series of tests at the University of California in Los Angeles (UCLA) by Dr. Lyman and his colleagues has shown that various externally powered devices, both electrically and pneumatically powered, tend to have relatively slow activity. The difficulties have been not only the delayed feedback, beyond normal reaction time, but the still motion involved in a relatively low-powered device. The patient opens a valve and gas flows, or he starts a motor and there is a whirring for another half a second before the action is completed, in contrast to the relatively instantaneous motions which he can obtain by cable control. The tests at UCLA and some others (specifically on artificial hands) at the VA Prosthetics Center in New York were described in "The Bulletin of Prosthetic Research" over a series of issues. These reports have clearly shown some of the limitations which must be recognized in making real improvements in the manipulator field.

I'd like to point up some of the problems, perhaps, in upper extremity prosthetics with a severely handicapped case, such as Mr. Wirta described. Such a case does not have the below-elbow muscles to control a simple myoelectric hand. We have here a veteran who was tested rather extensively in the VA Prosthetics Center. This is an example of shoulder disarticulation on the left side with just the remaining movable acromion process, or shoulder tip, and he has a very short stump on the right side which is capable of some motion but not enough to drive a conventional artificial arm. The stump motion and strength are sufficient to operate gas valves or perhaps electric switches if the clinical team members wish to do that.

There were studies of upper-extremeities biomechanics at UCLA several years ago. Similar studies were reenacted in the VA Prosthetics Center to study the forces and motions needed in the various activities of daily life — combing the hair (fig. 29) and a wide variety of other activities. The concern, then, was that a well-rehabilitated amputee could take care of himself adequately by prostheses, and would also be able, by suitable vocational guidance, to find an appropriate job.

Out of the fundamental studies, partly based on work by Dr. Marquardt on the original Heidelberg gas-powered arms, other arms were designed by Dr. Kiessling of the American Institute of Prosthetics Research. They were evaluated for

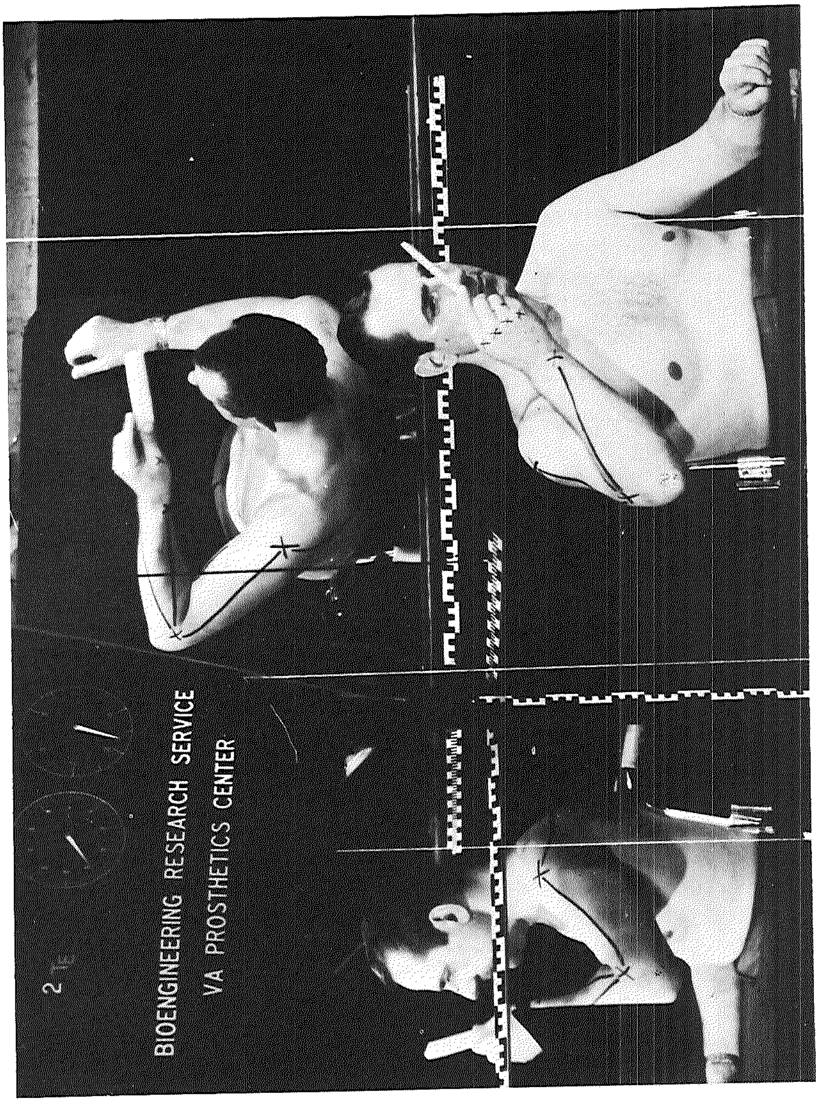


FIGURE 29

the amputee by using carbon dioxide energy from canisters carried on his back to provide elbow flexion on both sides, the operation of terminal devices, and, I believe, wrist rotation. In the case of the left arm, which had only the acromion process, you remember, the "fenestrated" socket is supported close to the neck and along the thorax, so that it remains stable while the acromion process moves under it, either up and down or forward and backward with respect to the socket. These independent motions can then be used to control a joy stick-type valve in two directions and two motions, thus giving some independent controls. On the patient's other side there are some valves in the cutouts near the upper portion of the right socket, which can be pressed against by motion of the very short humeral neck stump. So, again, he has several independent possible motions as by forward motion of the stump, by abduction of the stump, etc.

Part of the problem is to evaluate such a prosthesis and see if in fact it does any good. Thus, there has been devised a series of standardized objective tests: picking up objects of various sizes and weights, carrying out different functions such as eating and grooming, and so on. The patient was first supplied with the best body-powered arms available at the time, then trained, and tested. Next he was fitted with increasing numbers of power-driven components, trained, and again tested. Then he was refitted with the conventional arms to make sure that whatever improvement he had shown was not just due to additional training.

In the end, he was asked what he wanted to wear, in addition to the analysis of the objective tests of his performance, which included his ability to reach and to operate at various levels in front of the body, and so on. He elected to keep the auxiliary-powered devices even though he could do only a very few more things with them; he could at least do them more easily. Still, it is a major job for this patient to function effectively; he needs a lot of concentration because of the difficulties in control.

There was a meeting of a panel under Mr. Kay's committee last October to review seven different externally powered elbows, including the "Boston Arm," the "AMBRL," developed by the Army Medical Biomechanical Research Laboratory, the "Gilmatic," developed by a man who has been in the program for many years, the "AIPR" pneumatic, and several other arms. This led to an agreement that the AMBRL and perhaps the Gilmatic electric elbows were at the stage where 20 or 25 copies

of each should be obtained for wider tests. The panel felt that the Boston Arm was still very much at the development stage and required considerable effort to reduce cost and weight. There will be a similar meeting to review terminal devices (artificial hands and hooks) starting in March with the fitting of a series of patients under the supervision of the developer. A later meeting will be held to review and discuss the results and to develop criteria.

This panel is only one part of an organized program under the National Research Council, the Committee on Prosthetics Research and Development, which attempts to coordinate research by many agencies, sponsors, and laboratories in this field. There is another parallel Committee on Prosthetics-Orthotics Education, which carries out prosthetic education and tries to disseminate research information to medical schools, therapy schools, and so on, as well as county medical societies, national meetings, and elsewhere. Finally, there is a clear-cut area for increased sensory feedback, which has been a constant theme through this meeting. I have an old memorandum from 1955 on this topic. A Japanese team presented a paper on sensory feedback in artificial arms at the Hong Kong Pan-Pacific Rehabilitation Conference last summer, which excited considerable interest. The Boston Arm aims at tactile feedback of elbow position. Perhaps this whole area of sensory feedback will be revived and stimulated by a joint effort of the prosthetics and the manipulator people.

As a note of optimism, Mr. William Talley, who has been Chief of the Plans and Policies Division of our Central Office in Washington, which is concerned with the operational side of our Service, had an editorial in the fall issue (1968) of our "Bulletin of Prosthetics Research." This editorial discusses prosthetics research as a cost reduction factor. In it he points out that during the twenty years from 1948 to 1968, $20,100,000 was spent on prosthetics research by the VA. He has arithmetic to prove that in artificial limbs alone the VA has saved some $28,000,000 in operating costs and repairs. He points, in addition, to the tangible benefits of new devices at every level of amputation, new principles, better education, and so on. So we think there has been a reasonable return on the investment. We just wish a little more investment could be made in this area.

CHAIRMAN JOHNSEN: Any questions? I must limit it to two.

MR. HAMILTON, Institute for Defense Analyses: Could you give us some ideas of how many people in the country have limbs missing?

MR. KAY, National Research Council: 400,000 is the usual guess for amputations of major limbs.

DR. MURPHY: Of this total the VA is responsible for some 27,000 service-connected veterans, for whom we have a lifetime responsibility. These represent a very small fraction of the total amputees. There are additional veterans with nonservice-connected amputations.

The afternoon session was resumed at 1:00 p.m., Edwin G. Johnsen, Chairman, presiding.

CHAIRMAN JOHNSEN: Dr. Moe has a five-minute movie that he wants to show dealing with some of the work which is being done here at the Denver Research Institute. I guess while they are setting up the movie he can give us a little rundown on what it is.

DR. MOE: We have a project in cooperation with Rancho Los Amigos Hospital to develop a control system for the Rancho Electric Arm. One basic component of our control system is a small mechanical coordinate converter shown in figure 30. Its purpose is to simplify the commands that a severely disabled patient uses to obtain coordinated control of the arm. The film is an engineering documentary made to evaluate the coordinate converter. The patient is using a strain—gauge tongue switch as in figure 7 to control the coordinate converter. This device then translates the signals into the proper joint motions. It is a proportional system in that it has variable speed control.

QUESTION: What happens when you use the joy stick-type of tongue switch?

DR. MOE: We have not used the joy stick tongue switch yet at Denver Research Institute. They have had some experience at Rancho with joy stick tongue switches. We certainly are interested in it because it would make coordinated motion easier to obtain (fig. 31). Our objective in the movie was to find out what the system is doing now and

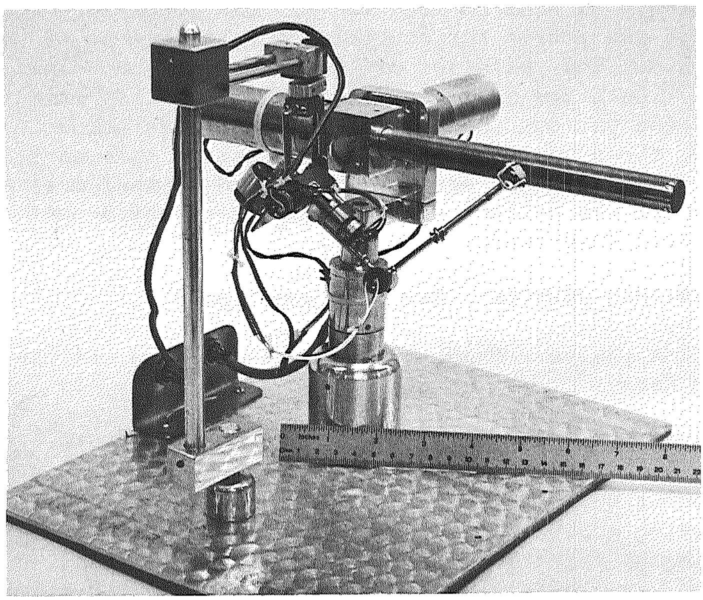


FIGURE 30

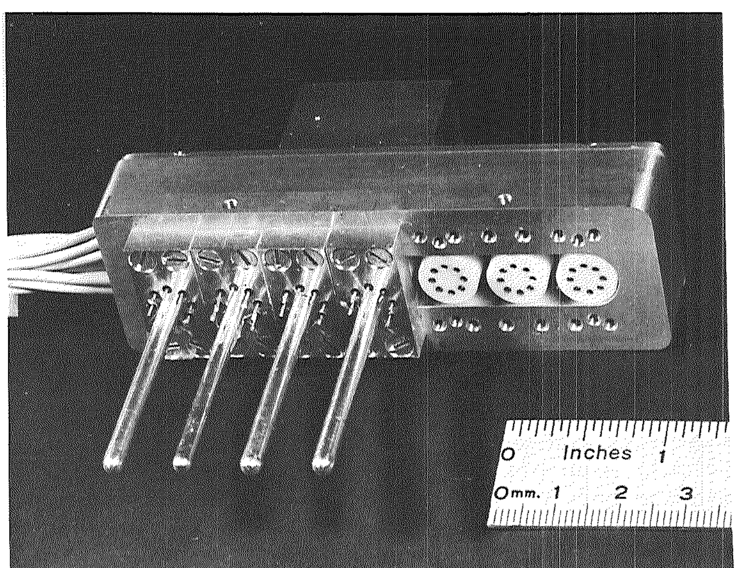


FIGURE 31

what changes we need to make in it. Our long-range objective is to use eye motion for control. But at this point we wanted to check out the operation of the mechanical coordinate converter. There are still some changes we want to make to control the various speeds of each joint more accurately. For example, the elbow elevation is too fast in this particular movie. These changes are being made. Note that even with this system the patient can get good coordinated motion with very little experience.

CHAIRMAN JOHNSEN: Any more questions?

Thank you very much, Dr. Moe. I will now call on William Kama.

MR. WILLIAM N. KAMA: I am a Research Psychologist with the Controls and Displays Branch of the Human Engineering Division at Wright-Patterson Air Force Base, Ohio. Today I'll be speaking about the research we are doing at Wright-Patterson in the human factors area. Currently, we are involved in two projects, remote-driving and television viewing systems. In the remote-driving area we have two experiments underway. In the first, we are comparing operator performance on two types of control systems — a joy stick and a multilever control. Basically, this is a comparison of a one-handed vs a two-handed operation. In the second experiment we are investigating the utility of auditory feedback for remote driving. Under one condition, useful auditory information is fed back to the operator, i.e., sounds of the vehicle's motor, etc., via earphones. Under a second condition, only white noise is fed back to the operator.

The second topic I would like to discuss is a technique for producing depth in television presentations. This recent technique is a relatively simple one and involves the use of a two-camera-monitor chain with a simple optical system, i.e., four mirrors. The arrangement of the optical system in front of the two television monitors is shown in figure 32. The two inner mirrors (DM) are set at an angle of 90 degrees to each other with the two outer mirrors (ML and MR) parallel to their respective inner mirrors. The observer then looks into the center mirrors and sees the image displayed on the right monitor only with his right eye and the image displayed on the left monitor only with his left eye. By adjusting one or both outer mirrors, the observer finds it easy to fuse the disparate views of the same scene and thus, obtain a strong impression of depth in the scene.

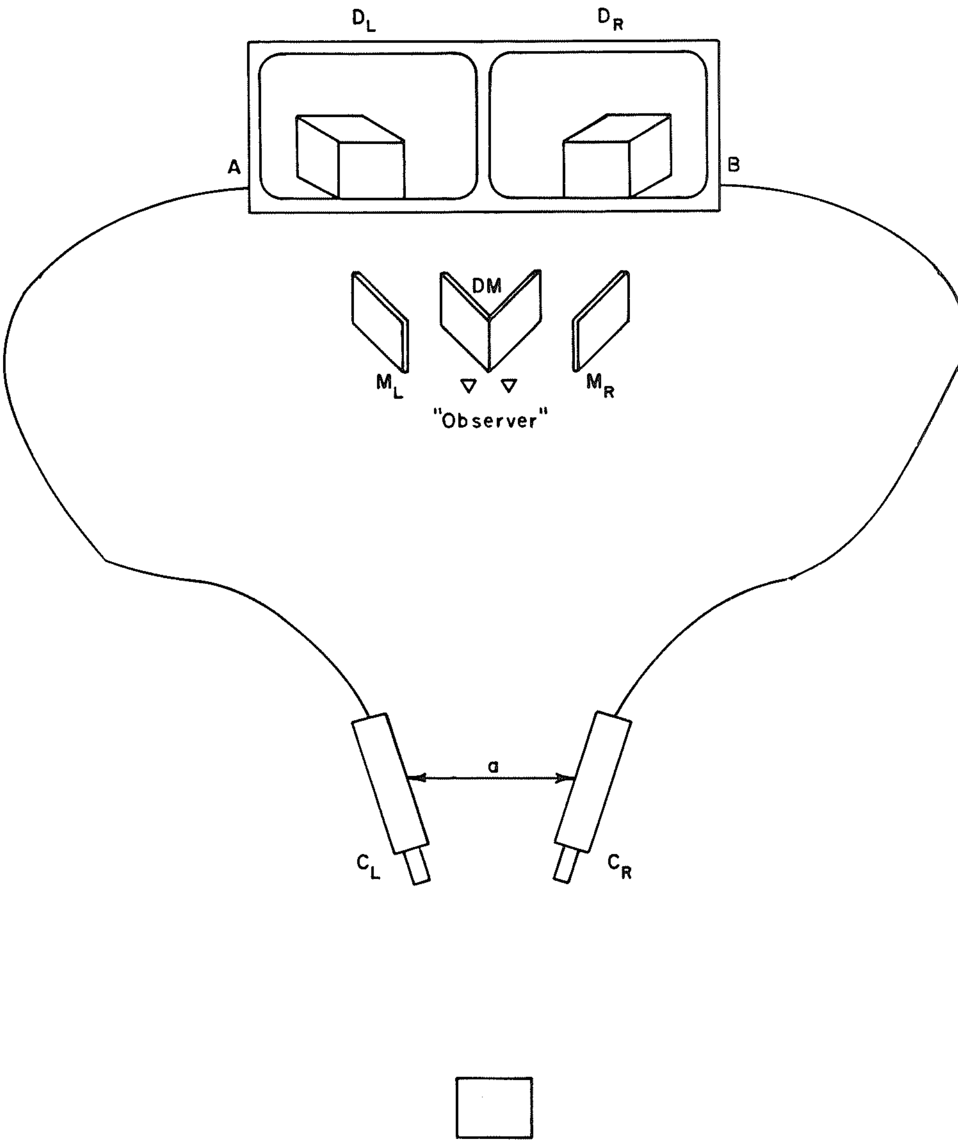


FIGURE 32

This technique is based on the principle used in the telestereoscope. The appeal of this system is that it doesn't involve much cost. In our research on remote driving for example, we assumed that there would be more than one TV system on the vehicle. Thus, the two TV systems already available can be used in conjunction with the optical system just described in order to obtain 3D information. The only additional cost would be for the optical system, and that would be nominal.

Since this technical development is rather new, we have not as yet obtained any empirical data regarding it. We intend to set up a research program to look at some of the problems that might be encountered, for example, how far can the cameras be separated or how large a convergence angle can we use before some distortions in the presentation arise.

So far we have used a camera separation of about 24 inches with a camera-to-object distance of about 20 feet. Approximately seven people have looked through the system with all seven of them saying that they had no problem in seeing depth. Primarily our subject matter has been stacked boxes. We place a small box on top of a larger box with the smaller box sticking out beyond the larger box about a fourth of its length. All seven persons who looked at this scene through our system indicated, quite strongly, that the smaller box was about to fall off the larger one.

CHAIRMAN JOHNSEN: Are those front—surface mirrors?

MR. KAMA: Right. All we did was to pick up four dime-store mirrors, 2 by 3 inches in size. In order to determine whether this technique would work, we took two different aspects of the same scene using a Polaroid camera, set up the mirror system, and placed the Polaroid pictures in front of them. After several attempts we finally managed to get depth. We therefore said, "If it works here, it should work with the TV monitors." We thought that we might have some problem with differences in alignment, resolution, and things like that, but we haven't had that problem at all.

CHAIRMAN JOHNSEN: Do you have a program lined up?

MR. KAMA: We plan to set up a program and will be looking at what effects camera separation and convergence angle have on the system. We also plan to look at this system in terms of reconnaissance. You may recall that during World War II they used stereo cameras to get good

depth relief of terrain and we think that this system can be used in the same manner.

MR. CHATTEN: Did you have any difficulty in adjusting the raster parameters, sizes, distortions, and so forth to make these match?

MR. KAMA: No difficulty at all. We simply adjusted the contrast and tried to get it focused about the same.

CHAIRMAN JOHNSEN: You didn't encounter any problem in getting them to register the same?

MR. KAMA: No. When I first started on this, I was discouraged by what I had read in Mauro's report regarding the problems of alignment, resolution, and things like that. However, we felt that it was worth a try, and it worked. It appears to have a lot of potential.

MR. FLATAU: Have you tested distortion of the spatial picture you get?

MR. KAMA: No. All we have done so far is to get someone to hold a rod in the field of view and have the observer direct the person holding the rod to move it to whatever position the observer desired. We increased camera separation and shortened the camera-to-object distance. In both cases this enhanced the depth effect without distortions.

QUESTION: How far away is the man's head from the center mirrors?

MR. KAMA: Presently we have him positioned right up at the vertex of the angle formed by the center mirrors. However, once they see depth, some of the observers have moved back about four or five inches without losing the depth effect.

QUESTION: You put your nose against that crack?

MR. KAMA: Yes, right here. Then after you obtain depth, you can move back. Of course we will have a viewing hood built so that you won't have to do this.

CHAIRMAN JOHNSEN: Thank you very much Mr. Kama. Dr. Farr.

DR. MARSHALL J. FARR: I am the Assistant Director of the Engineering Psychology Programs Office of the Office of Naval Research (ONR), Washington, D.C., and I am the Program Director

for the subprogram which we call "Augmenting Man's Physical Capabilities." I say physical because there has been some confusion generated at previous meetings like this, where the man-augmentation field has failed to differentiate between augmenting intellectual/cognitive ability, sensory abilities, and sheer physical abilities. Within the bounds of physical augmentation, one can conceive of three or four main areas of augmentation, and I would divide it as follows: augmentation of human strength; augmentation of human reach (and within this reach dimension one can include the entire field of coaxial manipulators and remote manipulators); augmentation of human endurance (which may correlate with strength in some ways, but not necessarily so); and augmentation of human flexibility/dexterity.

Many of our everyday tools meet these requirements. An electric drill, for example, is superior to the human arm; it can keep going round and round at a speed unobtainable by unaided man. And, even without a power source, you can accomplish a great deal with an ordinary hand drill, a screwdriver, or a pair of pliers. For this particular session, I will talk about the strength and endurance categories together, as represented by a system that is now called Human Augmentation Research and Development Investigation (HARDI-MAN), or the powered exoskeleton, which most of you have probably heard about. This device augments both strength and endurance, and I will give some brief history for those of you who are not thoroughly familiar with it.

The program started almost ten years ago, with a contract that was supported for several years by the Engineering Psychology Branch of the Office of Naval Research, by the Army, and by the Air Force, with Cornell Aeronautical Laboratories as the contractor for developing a nonpowered exoskeletal harness.

We come now to what happened after Cornell Aeronautical Laboratories proved the feasibility of a nonpowered harness which a human being could wear without substantially impeding his mobility range and flexibility. Following the Cornell study, a contract was let for prototype development and fabrication of a single, powered exoskeleton (fig. 33). This was intended to lead to a set of "mechanical muscles" that would actually augment a man's strength. The specification called for enough augmentation so that a man might easily lift up to 1500 pounds by use of this exoskeleton structure. He could carry it and support it at a certain height above the ground for a given time, enough to establish

the fact that the device is feasible. I won't go into these numbers now, but they were intended to show that this could be done long enough for a practical Navy and Army application.

The contract for this was let to the General Electric (GE) Company in Schenectady, supported by the Army (first, Army Natick Labs, and now, Fort Belvoir), by the ONR, and by the Naval Air Systems Command. An artist's concept at the beginning of the GE contract is shown in figure 33. It shows a photo of a manikin, about a foot high, wearing the harness in the manner originally envisaged for how this machine might work. You can see in the upper right and left corners where the manikin has stepped out of the structure, which was meant to be strapped around the waist. The design has changed rather substantially since then.

Figure 34 is an artist's conception, a little later in time, of how the machine might look. You will notice the protective gear around the head. Figure 35 again is an artist's conception of one of the possible jobs envisioned for the operator loading cargo onto a truck platform. The pack on the back of the man is meant to be self-contained. The first model, still in development, will have an umbilical connection. We'll plug it into a power source, so that we're not worried about the back pack now. That is for the future program, when the first model is finally completed and checked out to our satisfaction.

Here is a recent photo (fig. 36) of the first piece of hardware built by GE, showing, as you can see, a test leg. If it looks rather tremendous and heavy, that's because it is, since it is merely a prototype model. Within the next year we hope to develop an arm to correspond to the leg, and if funds become available, the entire full-scale device to be worn by a man could be available by the end of the calendar year 1970. This projection is optimistic.

Let me now give you, in a brief summary, the advantages of a system such as HARDI-MAN. I added on "man" to it to make it correspond to "Handyman," an earlier GE remote manipulator developed for work in "hot" environments. To present some points that may not have been made:

(1) The device is articulated.

(2) It involves a master-slave relationship. The master harness picks up movements of the limbs or other parts of the body and transmits proportional signals to the slave

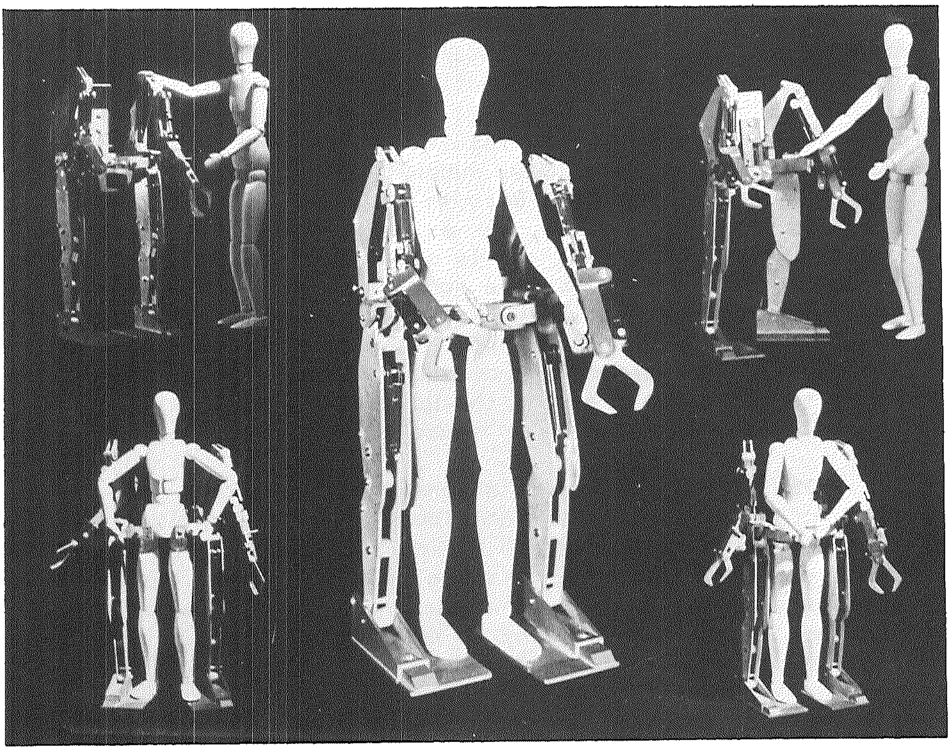


FIGURE 33

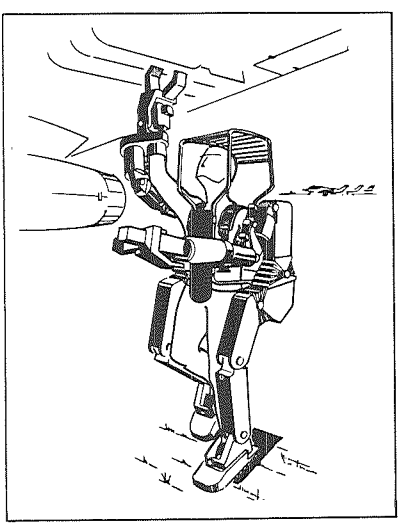


FIGURE 34

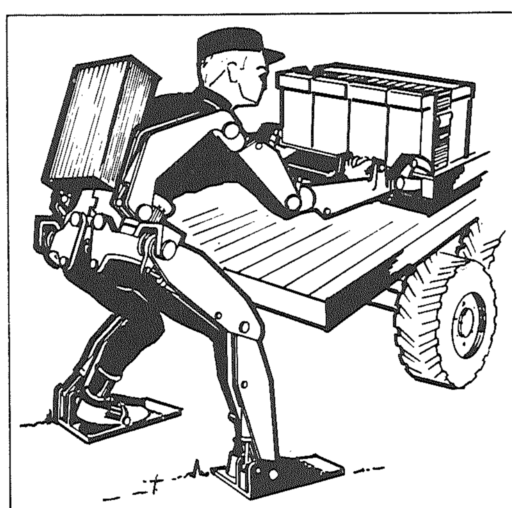


FIGURE 35

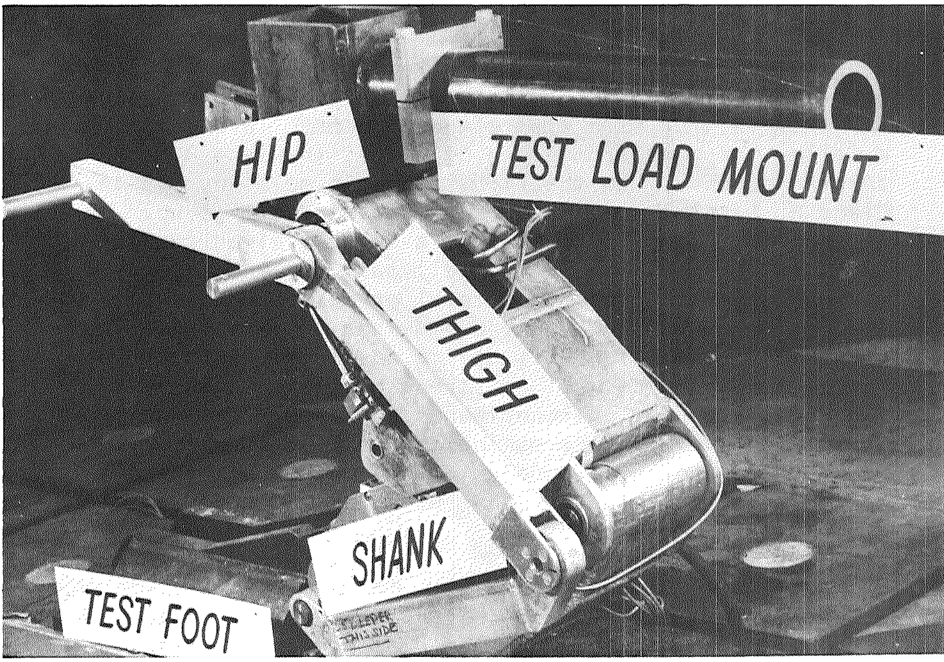


FIGURE 36

harness; the slave then takes the action. You have a "bilateral" force-reflecting servo system here. Bilateral in this sense means two-directional. The forces or resistances encountered by the exoskeleton are fed back to, and "felt" by, the man. The reverse is also true.

(3) The structure is powered for augmentation. The man does not feel the weight of the structure itself. It will have a force-feedback ratio of something like 25 to 1. Thus, the man will feel 1/25, roughly, of the forces encountered.

(4) The device follows the shape of a man. There are many useful reasons for this, some of which are empirically validated while others are not. The human being has a better feeling if the device is the same shape as his body. He knows where his two arms and legs are, since he has grown up with them. He also takes advantage of the fact that an operator should be able to master this device in what amounts to a negligible training time. Whatever he does in natural movement will be followed by the slave. There should be no really new learning necessary. The virtue of these natural

movements is that there is a lack of control-display-relationship errors.

Now, in the field of human factors, control-display errors are a frequent problem encountered, and responsible, for example, for some aircraft accidents. To explain: take a fellow who goes from plane to plane; in Plane A, the turning of knob x to the right makes it go down, but in Plane B, turning knob x to the right makes it go up. In times of stress or distraction, a pilot trained on Plane A who changes to Plane B may well turn the knob the wrong way and thus commit a fatal error. There is no problem with HARDI-MAN because nobody has to learn anything unusual or atypical. This device, as I said before, enhances endurance as well as strength. Take away the master and the slave from the contiguous coaxial relationship and you would have a remote manipulator. Even in this remote case, there are advantages as to why one would want the manipulator to be in the shape of a man, even at the slave end.

(5) With the HARDI-MAN concept one could attach any number of terminal devices, either to the feet or to the hands. The hands could have an electric drill attached instead of just a gripper arrangement. The feet could have a snowshoe kind of arrangement, so that you could actually screw on a different set of feet for travel over varying kinds of terrain, which would make this thing very adaptable.

Briefly, these are the problems that we hope the future will solve with HARDI-MAN: we hope to go, as I say, from an umbilical to a self-contained model; and we hope to get better, more streamlined packaging. The model is developing so that it is going to be wider and bigger than we thought. The original specification called for it to fit through a doorway of a certain size; unfortunately, I don't think it will make that. But this is, after all, a prototype model to demonstrate the feasibility of the approach and to iron out certain human-factors balance problems.

Now, some of the possible applications. Conceivably we can replace forklift trucks or devices of that sort in those relatively confined spaces where a forklift truck either cannot operate or operates ineffectively. The cargo-handling applications are obvious in many other domains. Furthermore, there is a possible underwater application.

The Litton Space Systems people several years ago were talking about proposing to modify for underwater applications a space suit they had developed for NASA. The result was seen as a self-contained, constant-volume, articulated suit at one atmosphere. Now, if this kind of concept were developed into a powered-servo-boost system, you could foresee a number of underwater applications. When this device was hydromechanical it could have been put into water and worked with very little, if any, modification. There will be some complications now with the electronics involved, but they could still be sealed off and made to work in such an environment.

CHAIRMAN JOHNSEN: May I ask a question? About a month ago the head of the Physical Medicine Division of the Holy Cross Hospital at Silver Spring asked me if I knew of any work that had been developed which could be applied to stroke patients who had a paralysis of one or the other leg. He told me that if we could get powered braces for stroke victims, so that they could start walking around, their rate of recovery would improve rapidly. Now, it sounds to me like you have already got it here, haven't you —these powered legs you have been developing? You could miniaturize, because you don't need the strength that you have there. Haven't you already developed a lot of this technique?

DR. FARR: Right now the person's own motion is required to initiate and follow through on the motion of the slave. Given an EMG pickoff you do not need actual motion, you just need electrical signals. With a completely paralyzed leg which cannot generate its own forces, you would need something like an EMG pickoff from a proximal body site in order to start and keep the thing going.

CHAIRMAN JOHNSEN: In the initial phases, if you can start getting your legs working after a few days or a few weeks, doesn't it begin a pick up itself?

COL. BROWN, Fitzsimons General Hospital: For some types of strokes that is true, and your master-slave concept could be applied through the type of device you are describing. It would just be another circuit there, and this would certainly be of aid in rehabilitating certain types of strokes in similar conditions.

MR. KAY: There has been some work done at the University of California on this type of device by Professor Magee, but when he is working with a single leg you have to put in

certain inputs to that leg, synchronizing with the action of the normal other leg.

CHAIRMAN JOHNSEN: I should think we would be able to include a small special computer to get the two working together.

DR. FARR: Of course, for standard movement it would be easier to program this kind of thing. Perhaps something like the patterning, discussed earlier by someone else, is possible. It is movement superimposed from without on a limb or the entire body. Patterning is supplied, as I understand it, to people who are neurologically damaged — brain damaged for the most part — who have difficulty but not complete lack of ability, in coordinating movements. And by having other people physically move their limbs and entire body in a particular patterned fashion, hour after hour, it has been reported that the person will then learn to do this by himself without the aid of some motion imposed from without.

MR. MOSHER, General Electric Company: Dr. Lieberson has done some of this work at Hines (VA). He was using only the hip. He needed external power on the hip and this involves other problems. Gait, for example, has a definite pattern. It seems it would be easy to go ahead and program this, but if someone steps in your way, immediately there are other problems, such as balance.

CHAIRMAN JOHNSEN: Wouldn't HARDI-MAN have the same problems? I mean, how do you stop the thing?

MR. MOSHER: If the one leg is good, you can take this motion with an exoskeletal control for getting position signals and echo it into this artificial powered leg. You could superimpose biases on this cycling, the action of one foot as compared to the directing motion of the other foot or leg. This technology shows you can control balance if you get along with certain distortions of man's orientation with respect to the vehicle. One other important thing. We are all really talking about and around the fidelity of control between man and the end effect, and this equipment demonstrates the ability of having the speed, strength, positioning, and force fidelity needed. I am convinced that it can be done. If you want that device developed to let the guy get a patterning motion and develop this neuro-learning again, there is no question that it takes time and effort to do something like this.

DR. MURPHY: Cornell Aeronautical Laboratory put in a proposal to us to work with the VA Hospital in Buffalo on adapting their control brace on this problem of training disabled people. This involved exercising them or using the control brace for objective measurements of the strength of various joints. However, we were never able to finance this and we are not sure it was a good idea to begin with, but they thought of it several years ago. As far as I know, nothing tangible developed except that we suggested they work with the brace maker at the VA Hospital.

I would reemphasize this point on the variety, even on a simple thing like walking. If you are walking in a straight line on a level floor, you may be able to use mirroring to the other leg, as Mosher suggested, with some displacement of phase; but if you want to turn or go up and down stairs or step over a doorsill, the problem reaches another level of difficulty.

DR. MOSHER: Please, don't be too negative about the idea. Otherwise you might be precluding the understanding of how amazingly adaptive the human body is. You can get along with these distortions. As an example, let's take a peg leg. He can turn around with his one good leg, and so on, right? What we are trying to do is improve this ability.

DR. MURPHY: One of the things about the peg leg is that the above-knee amputee has a direct extension from his hip joint, as Norm Wiener pointed out. The patient knew where the tip of the peg was by perception from his hip joint, and he knew from the pressure on the stump whether it was weight-bearing or not. As soon as you introduce artificial joints at the knee, and perhaps the ankle, then you are adding joints about which he does not know. That's why I say there is another level of difficulty.

MR. FLATAU: This is true if it is an open-loop device. If you close the loop in appropriate fashion, you can still maintain the stiff feel to the stomach, even when the leg is articulated.

MR. MOSHER: Remember how many closed loops there are in a human leg or appendage when you try to duplicate it. There are many. The artificial joint, you see, acts as a filter to some of these loops. That's the problem.

DR. FARR: The human being is capable of learning complex relationships, unconsciously and consciously, that are

hard to believe. After all, a human being should not be able to play a piano like a virtuoso, but he does. In the same way a bumblebee shouldn't be able to fly, but he does.

CHAIRMAN JOHNSEN: Thank you very much. Let's go to Andy Karchak from Rancho Los Amigos.

MR. ANDREW KARCHAK: We have had two presentations, one of the master-slave exercisor from Rancho, which is an innovation of the electric arm, and the other showing a patient functionally using the arm. What I will review will be the developmental stage that we went through in evolving some of the techniques used in making it successful. For those of you who are not familiar with Rancho Los Amigos Hospital in Downey, I will indicate that it is a country hospital, which during the polio epidemic became a respiratory center for the southwestern part of the United States. They collected a great number of polio patients there, and as medical knowledge in the treatment of patients with polio developed, along with respirators, it began to save many lives. We wound up with patients in varying degrees of paralysis, all the way from something simple to extreme quadruplegia, where they had nothing below the neck. I mean just complete paralysis.

Naturally we had some responsibility to try to help them out in their rehabilitation. We then began to think of the concept of applying external power to these patients, in the form of, say, prehension first, taking something simple. The patients who had affected finger flexes or extensors were fitted with hand equipment, using a simple three-jaw chuck-type of prehension rather than going into the complexity of trying to duplicate the finger motions, which required a single activator.

Well, the power source used at the time was pneumatic because Dr. Marquardt in Germany at that time was using it fairly successfully in prosthetics on his amputees. During the beginning of this program the individuals were fitted for prehension and initially used light-walled aluminum pistons, so that they could be placed on the splint. Shortly after that, the McKibben muscle was developed. I don't know if any of you are familiar with it, but it is one of those weaves, similar to the Chinese finger-trap you put on your finger. If you pull down, it tightens down on your finger, if you put a bladder inside and inflate it, it contracts. The desirable feature of this device is its similarity to the anatomical muscle, starting out with a lot

of force, which dropped off when the muscle was contracted to full extension.

This was placed on several hundred people at the time, and proved so successful they began fitting patients with a little higher degree of paralysis. People were using it every day and it was giving them function. Next, they began fitting the type of patient who wore what was called a ball-bearing feeder, now known as a horizontal-arm support.

These patients were the type who had a certain amount of residual arm and trunk motions. If you supported their arms against gravity in some sort of a device, they could rock around and get functional motions. Now, when you get a marginal type of patient like this, you begin to look at the application of external power, which is a little higher level of paralysis. They again used artificial muscles on this unit, which was nothing but two arms that rotate around the vertical axis. One is the proximal arm that attaches to the wheel chair, and the other is the distal arm that has a tray in it which supports the arm. The tray will rotate both about the vertical and horizontal axis.

After they had accomplished prehension functionally for the patient, they went on to external power on these types of devices by putting a muscle on each segment of the arm, pulling it in, and letting gravity take it out when the muscle was deflated. As they became successful in doing this, they began to think of the higher levels of paralysis, and slowly they worked up towards the individuals who were complete quadruplegics, patients with nothing in their upper extremities, and generally nothing from the neck down. Some of the polios had small flickers in their toes or maybe a finger, which would produce a little extremity motion. These motions were generally harnessed for their controls.

There were two problems, though, we found in the pneumatic system with this type of patient. First of all, we wanted to correct the customized fitting required. When you are using extremity motion such as a toe flicker here, or have some motion around the head that you can utilize, you have control systems strung out all over the individual's body, and it is different for each individual. There was another problem. We could fit these at Rancho fairly well, but people throughout the country were having difficulty in fitting them. Then a further problem arose. These patients used electric wheel chairs in order to get around, because there was no other way they could move about in the hospital or in their home. The wheel chair is fitted with two large

automobile batteries — six-volt batteries — and there is an abundance of energy even for propulsion. They can generally run a wheel chair two or three days without charging. The power unit requirement of an arm brace, in the application of external power to these patients, would be very small compared to that used for running the wheel chair.

Then we began to think in terms of using an all—electrical system. We were using CO_2 systems to power orthotic applicances and the electric power on the bottom of it to drive the chair; we thought we would combine the unit to make it all electric. We also kept thinking of future control systems which probably, we felt, would be electrical. During that time, when we were about ready to make the change, we were thinking in terms of what we would use by way of joint motions. Would they be the same as the pneumatic arm? When we looked it over we thought most of the joints were fine but the pneumatic arm did not have a humeral rotator; it had pronation and supination and it had all the other joints.

Just about this time, James Reswicke from Case Institute was ready to get started. He was looking at the same problem regarding joint and torque requirements, and individually, without knowing it, we came up with just about the same specifications. The only difference was that in his humeral rotator he did not provide joint motion through the center of the arm, which makes things a little simpler to build. You didn't get a pure rotation through the arm but you rotated around an arc. The prototype model was just a rectangular bar-stock, cross-sectional area, on which we mounted motors, and we ran this through a testing procedure just to see how they worked. We also placed a few patients in them as a tryout.

Finally, we developed a unit with seven joints, which are not as anatomical as we could make them. The first joint at the top is a rotational one through the vertical axis about the shoulder, which moves the arm in a horizontal plane. The first models we built had adduction and abduction motion in the unit at the first joint, the second one being the humeral flexion, and then the humeral rotation, elbow flexion, forearm pronation, supination, wrist flexion, and finally prehension.

We decided this would be a good system initially but it offered a problem. There is one thing these people do a number of times in their daily activities; they live in a

wheel chair and they have a lap board mounted there. They pick up objects and transport them across their lap board, such as feeding, doing tile work, or whatever the O.T.'s find for them to practice on, and they do this several times a day. If the first joint at the top of the shoulder is adduction and abduction, this simple motion becomes a complex motion of several little joints simultaneously at varying velocities, and it creates a tremendous control problem.

Since at the time we were using straight switching systems, we found that this was almost impossible for the patient to handle. The only solution was to change that first joint at the top from the adduction-abduction joint to a rotational one through a vertical axis, so that they could push one switch and solve the complex problem. This does restrict range of motion. We thought we would leave it out until our control system had been refined.

About that time, Dr. Nickel, our Medical Director at Rancho, approached us about using the tongue. A lot of people wonder why we use the tongue. When you consider that here we have seven joints of motion and 14 channels to control bidirectionally on the arm itself, plus four channels of control for the wheel chair (a total of 18), you can appreciate the control problem. This is especially true when you are dealing with an individual who is completely paralyzed from the neck down. It is not a trivial problem, but the tongue is a very educated muscle.

When the idea was first presented to us we thought it would be objectionable to the patient and he would reject it. The first time we tried the idea out it was fabulous. We tried it in the shop, and we just had an improvised type of tongue switch which we made ourselves. It worked perfectly and solved the problem of custom fitting.

Generally, a severely paralyzed person has a tongue function left which can be used as a control source. In the number of years we have been fitting these arms, we have found only one case, a stroke patient, who could not control saliva. His tongue was impaired, and this would be the one type we couldn't fit. But it worked so well on the greater majority of our other patients that we think of it as a complete success. It is not custom-fitted, because you can position that tongue switch in front of any individual and they can control it. They very quickly learn to operate it. The first joint on the arm is controlled by the first tongue switch bidirectionally up and down. If you push it up, your vertical joint will go up; if it is pushed down, it will go

down. So it becomes somewhat easier to learn in that sense.

We have been very successful with it because it can span the number of degrees of control we need to move the arm brace. We are going into future systems, as Dr. Moe was telling you. An intraoral-control system that is being worked on will take the tongue switch and place it inside the mouth on a bridge with pressure sensors on it, which will telemeter out the information to the joint. As you press on these sensors, they will rotate the arm joints.

One of the big questions is in regard to cost. To keep one of these patients in the hospital, or other institution, costs about \$68 a day, although that figure is probably higher now; this amounts to over \$2000 a month. If you can fit a patient with a device like this in a chair and send him home with an attendant, the cost will be about \$450 a month.

You might say, "All right, he can go home anyway, even if he is paralyzed." He can, but he needs somebody to constantly watch him. If the patient is in bed, you can't leave him too long. On the other hand, if he is in a chair he can do little things for himself, even though he might not be able to get out of it alone. If you can leave the patient alone and give him a degree of independence, this is in a manner some form of rehabilitation.

We have one girl who has her own little business now, a telephoning service. If this becomes successful, she will earn her own living. To even think of rehabilitating persons at this level, where they can get off the taxpayers' backs as far as supporting them is concerened, is really a remarkable thing.

We have 16 fittings now, with two more in the process, and we are trying to get information to the physician and the occupational therapist. We are also working to get some courses, probably at N.Y.U. or Northwestern, to teach people throughout the country to become more proficient at these fittings. These can be installed by orthotists and applied to a patient anywhere in the country. The only customized portion of the fitting is in the hand splint. The patient won't tolerate the hand splint unless it fits perfectly. The total cost of putting one of these patients in a wheel chair is \$3700. The wheel chair cost is a thousand. If you subtract that, you are at about \$2700 for adapting this to the patient and anybody can do it throughout the country,

provided you have an orthotist to make the hand splint for you.

CHAIRMAN JOHNSEN: Any questions?

Thank you very much, Mr. Karchak. Dr. Brown is our next speaker.

COL. PAUL BROWN: I am a little out of my natural environment in this group. I am a surgeon, Chief of Orthopedic Surgery at our local Army Hospital. My specialty is reconstructuive surgery of the hand. Therefore, I am at least on the perimeter of your interests and I have been fascinated with your approach to your hand. It has become increasingly clear to me that what we are talking about with teleoperators and manipulators are imitations of the human hand. It seems to me that it would be appropriate to take a better look at what we are trying to accomplish. It may be that we fail to recognize some of the problems we are inheriting in our attempts at this imitation.

As a hand surgeon I have little to do with teleoperators, but I have a lot to do with hands. I would like to show you a slide of a reconstructed hand (fig. 37). This reconstructed hand is in a normal position of function, which all of us use in our everyday life. This is what we are striving for, I in my way and you in yours. The problems I encounter are certainly different from those that you have to face, but in many ways we take the same route.

Possibly we haven't given enough consideration to the numerous and complex functions of the hand. Even though this is my life's work, I am still finding out every day that there are new functions a particular patient may have thought of or had need for that have never occurred to me before. To break them down — and there's a lot of historical background to cover — hands have figured very strongly in all religions as far back as recorded history. They also have a certain mystical significance. Special attributes have been given to the hand. For instance, the concept of the healing hand, which I as a surgeon know is a complete myth, but which has persisted in our mythology — the healing hand of the physician, the healing hand of the faith healer, or saint. These are all very much a part of our concept of the hand.

We use hands in communication all the time, and this is tied in with symbolism. Every culture, every nationality,

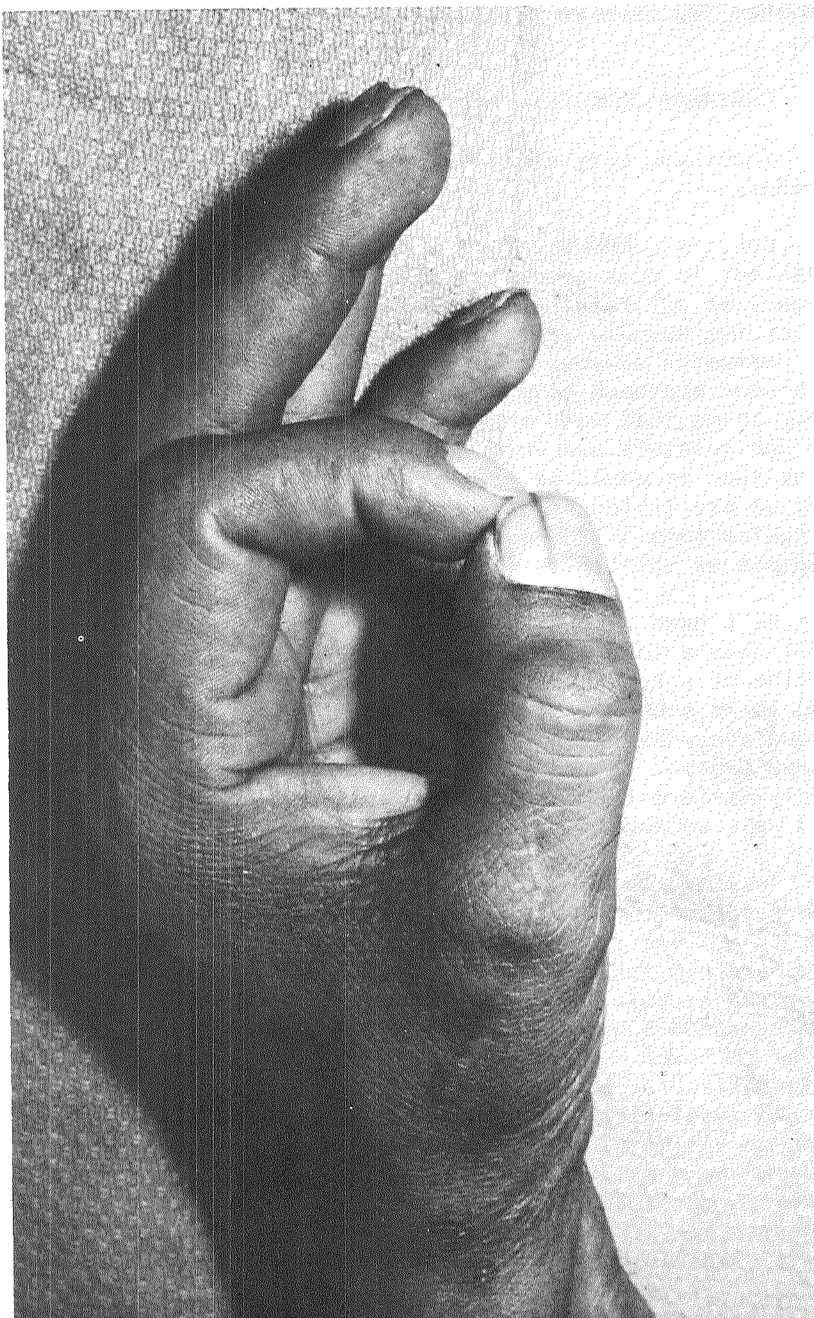


FIGURE 37

and every ethnic group has its own communicative uses of the hand. There are certain gestures that are almost universal. I suppose most of you saw the picture of the Pueblo prisoners taken in North Korea. They were making a certain gesture that was recognized all over the world and probably has been for the last few millennia. This is both communication and symbolism. Hands have a great cosmetic significance. I have to approach the female hand patient far differently from the male. With the male, it is primarily a question of function. With female, very often the cosmetic requirements override the functional requirements, and, of course, this is tied up with sexuality, and all sorts of other things.

CHAIRMAN JOHNSEN: That is one way to get a program going.

COL. BROWN: When we are talking about real hands, these are real considerations, and then, of course, the last and probably the most important are the functional considerations of the hand. Here you and I come together, in what we are trying to get this hand, this wonderful tool, to do or to perform for us.

When we consider the hand we must include the entire upper extremity, the arm, the forearm, the shoulder, and the elbow, even though for all practical purposes, the only function of the upper extremity is to put the hand — this terminal device — in a position where it will perform the tasks we ask of it. The shoulder and elbow are tremendously complex joints, but their function is secondary to the positioning of the terminal device, while the whole system, of course, is one of joints and levers under a central control. Basically, in the hand there are two systems we have to consider, the sensory and the motor system. The two are distinct in many ways and yet they are tremendously interrelated and, in certain specialized pathologic conditions, we can't separate one concept from the other.

The motor function, to which most of your endeavors have so far been directed, is really a wonder system, when you consider the wide range of forces and the many ways in which they can be applied by the hand. The contrast is great between picking up something as fragile as an eggshell, then using the hand for very gross and strenuous tasks. Here, we are getting into an area of misunderstood and poorly covered fields. It has been said, I think by Schopenhauer, that the hand is the outside brain of man.

This is just another way of saying that, lacking some of our central sensory systems, the hand may act as a substitute; certainly in the blind person reading Braille we have a wonderful example of this.

Now, consider what the sensors in the fingers do. They can discriminate pin pricks from gross touch. They can determine vibration. They can discriminate very finely over a temperature range. And they have a two-point discriminatory ability which varies in degree, qualitatively, from one area of the finger to another and from one finger to another, just as it does throughout the entire body. In fact it is in the tactile pads of the fingers that this two-point discrimination is most highly developed.

As a part of this, remember that these finger pads, these outside brains of man, have attributes that we don't find elsewhere. It is a self-moistening texture, and in a normal hand there is always a film of moisture overlying these sensors. It controls its own temperature and operates over a rather narrow range, if it is to operate well. It replaces wear and tear, and has a useful life of about 70 years. I think it is pretty hard to manufacture a machine that will fulfill these specifications.

Coordination and control are extremely complex, as we all recognize. Acting on, and in the hand, there are over 40 motors, any one of which may operate in combination with any other or groups of others. So you see the combinations — I am no mathematician and I wouldn't think of figuring out what they were, but they are tremendous and they are significant. All you have to do is look at somebody using their hands, even in a mildly complex task, to recognize how tremendous these combinations are. The intricacies of just tying a necktie or a shoe lace, if you watch somebody's hands and try to analyze what they are doing here, are astounding. You would have a devil of a time analyzing this on any type of a graph or with a formula. The hand can be used to exert very strong forces — karate actions or changing a tire — yet at the same time it may abruptly revert to the finest, most delicate functions such as playing a musical instrument. What's more, it can make this change of pace with amazing ease. My attempt, then, has been to give you some of my appreciation of what a tremendously complex tool and organ you are trying to duplicate.

I would also like to say something about the application of some of the things you are doing to our everyday medical problems. We have what can be called a rehabilitation paradox. To illustrate this, a couple of weeks ago I spent some time with the parents of one of my upper amputee patients explaining to them why the Boston Arm, which they had read about in "The Reader's Digest," was not going to be fitted to their son. They didn't understand. They knew what marvels medical science was turning out and they asked why I persisted in fitting a crude prosthesis, which hasn't been much changed in the last century, to their son, when all these electronic marvels were available. The point is, there is a tremendous gap yet between the producer and the consumer, and I have to deal with real people and real problems. By this I don't mean that yours are unreal, but they are different.

Most amputees with an amputation above the elbow never wear the prosthesis we fit to them, regardless of how hard we try to train them. Our success rate with even these simple devices is very small. If I can't make such a patient use a crude tool, I am certainly going to have difficulty in getting him to wear something as complex as a myoelectric arm. I am convinced that we're going to have this type of workable prosthesis. Although I recognize the value of a favorable press release of the kind of thing you are developing, please remember that if it's too enthusiastic, it may do the patient a disservice. Thank you.

COMMENT: I got very interested in making an artificial hand once, and I thought I had worked out a way to do it but I have never tried it. In the skeleton hands it appears that you don't really have a hinge at the joints; in other words, the bones slide over each other rather than hinge.

COL. BROWN: Indeed they do.

QUESTION: Is that an important distinction, or would a hinge be adequate?

COL. BROWN: A hinge is adequate and we are proving this in our artificial siliconized implants. For instance, to replace degenerated rheumatoid joints, we are using a flexible rod which, for all practical purposes, functions as a hinge.

QUESTION: If we made a hand that was one-tenth the size and was controllable as a master-slave or computer

controlled, would it be useful to you as a surgeon? In other words would it work scaled down by some factor ten to twenty times?

COL. BROWN: Theoretically, yes. For instance, in some of the new forms of microsurgery, where I operate under a microscope in repairing fine nerves and arteries, I am handicapped by the grossness of my armamentarium, the instruments, and the microscope; I am also handicapped by my own tremor, which I know is going to advance with age. If you could damp this out, if you could make my motions with surgical instruments more finite, more controllable, then conceivably this could be a great help in refining my surgical technique.

QUESTION: Basically, though, there is a substantial need for it as a commercial venture. Just to get some feeling, how many of them would be needed across the country? Do you have any rough idea?

COL. BROWN: Theoretically, X-number. One of the biggest problems is dealing with the temperament of the surgeon. A lot of us are prima donnas and we are not about to recognize that any machine is going to supplant our wonderful healing hands.

MR. FLATAU: I wonder if you can help us a little bit. We are trying to do what a good hand does — 22 degrees of freedom — with one degree of freedom, which is pretty bad. Of course, now, if you can go to two degrees of freedom we can improve enormously. Then let me ask a further question. If you had a mangled hand and you were given a choice, that is, you could only restore two or three degrees of freedom in two or three muscles, which ones would you choose — what motions would you prefer?

COL. BROWN: With every mangled hand that I have to treat — and I am confronted with several hundred out here at Fitzsimons — I start from this premise: is the hand as good, or can I make it as good or better, than a prosthesis? This is the basis of our plans for reconstructive surgery. I can never take a damaged hand and return it to normal. That is absolutely beyond my capability and, I expect, always will be. So there are degrees of return of function — what represents a tremendous gain for one patient may prove a complete failure for another because here we are dealing with the rather mystical, poorly understood concept of motivation.

This is an all-important aspect of any type of rehabilitation (motivation) — how much does this patient want to do with what he's got. The hands that you people are making are tremendously useful as they are now. Any greater degree of freedom, sensory capacity, and motor variability which you can add is a great step forward.

MR. FLATAU: You didn't answer my question, but I suppose the answer is not that simple.

DR. MURPHY: You remember Dr. Bunell, just before he died, had completed a manuscript for our magazine "Artificial Limbs" on reconstruction of partial hands, and the final decision of whether to go ahead and make a wrist amputation if the hand was too badly damaged. His major point, it seemed to me, was that if sensation was lost he might as well go ahead and amputate. If sensation was lacking, it might be dangerous, the patient would injure himself. But he had a variety of ingenious operations to give at least some degree of gripping force, deepening the cleft between the thumb and the hand, for example. His main goal, of course, was to try to get the three-jaw chuck prehension, index and middle finger against the thumb, if at all possible.

COL. BROWN: And yet we know if we have a hand that is anesthetic, for instance, which still has good motor control, the patient can substitute with his eyes for his lack of sensation. Such a hand is no good in the dark, but if he can use his eyes, he has a substitute sensor.

QUESTION: This is a little bit out of our field but in a sense an information processing problem. You mentioned the tie. The other day my daughter wanted to know how to tie a necktie. I found out I didn't know how to tie a necktie, but my hands did. So, essentially, my question is, when you work on these reconstructed hands, do they then get these neural patterns established again so they can do these semiautomatic operations?

COL. BROWN: The younger the patient, the easier it is because children are unprejudiced. You are set in the way you tie a tie, that's why you don't know how to adapt. You have to change your programming, which at my age is a painful process and sometimes impossible. But a child can do this with tremendous facility.

QUESTION: So these young patients from Vietnam, they can get back to semiautomatic?

COL. BROWN: Depends on how complex their problem is, and generally they are very complex. Therefore, we have a whole battery of people, the physical therapist, the occupational therapist, sometimes the family, the doctor, and the nurse, contributing to help this patient learn to use his altered hand, set up new control pathways, and block out a few switches and put in a few more. This is practice, practice, practice, with educated training. Some make it to varying degrees of success while others don't.

CHAIRMAN JOHNSEN: Thank you very much, sir. Mr. Hawkins, we'd like to hear about robots and pattern recognition.

MR. J. K. HAWKINS, ROBOT Research: You have heard some very good talks on solid developments in the hardware area and valuable research work being done. I will provide a change of pace by engaging in some pure speculation. What I thought might interest you is to report briefly on a panel session entitled "Human Augmentation through Computers and Teleoperators," held at the Fall Joint Computer Conference (FJCC) in San Francisco last December, in which several people here participated. The purpose of the panel was to set the stage and establish some of the parameters that surround possible applications of teleoperators in labor amplification, or human augmentation through the use of teleoperators and computer control systems.

The panel addressed itself to a problem posed by Art Critchlow, its organizer and chairman. Ed Johnsen here discussed the problem of teleoperators. Tom Sheridan, who is also here, talked about man-machine relationships. Others discussed communications and systems aspects. I considered how the present state of image processing or automatic pattern recognition would or could play a part.

The kind of system that was postulated was a very large central computer, a number of displays located with the computer, and operators who could, through the computer or directly, view what was going on at a large number of remote stations. There was presumed to be a variety of types of remote stations, each one mobile to some extent and also capable of performing various operations. We took some specific examples just to see what the parameters of such a

system might be. The kind of thing under consideration is touched upon briefly by Jim Nevins, talking about the computer-supervised manipulator. Here, sometimes at least, the remote manipulator could be under direct computer control without the operator on line, and the kind of tasks we had in mind were compatible with such a scheme. There are jobs going begging in many areas simply because they are so undesirable. Carl Flatau, I think, mentioned coal mining as one that few people care for.

To be more specific, the change in operating mode is depicted schematically in figure 38. Here the concept of an individual worker controlling a tool to perform a task at a particular location is labeled "Present." The concept of a remote work station with an appropriate tool performing its task under the general direction and control of a computer and human telesupervisor, which are time-shared among many such units, is marked "Future."

The question was, how would a system of this sort actually be made to operate, and what constraints would one impose upon it? The two things that seemed to emerge most strongly were first, that the communication links would have to be very low bandwidth, on the order of voice-type communication channels. Therefore, one is limited to applications such as space or underwater where bandwidth is constrained, or where the economics of the situation do not require an operator on line at all times. In other words, if we are, indeed, augmenting the ability of an operator to do a task, it does no good to keep him on line with a single task. That simply places a complex link between him and the job. Hence, he must be time-shared. The second point follows, namely, that we must have a certain degree of automatic, independent ability on the part of the remote teleoperator for short periods of time. The periods may be minutes or seconds. In any event, if the unit gets stuck or needs help, it can call on the central controller.

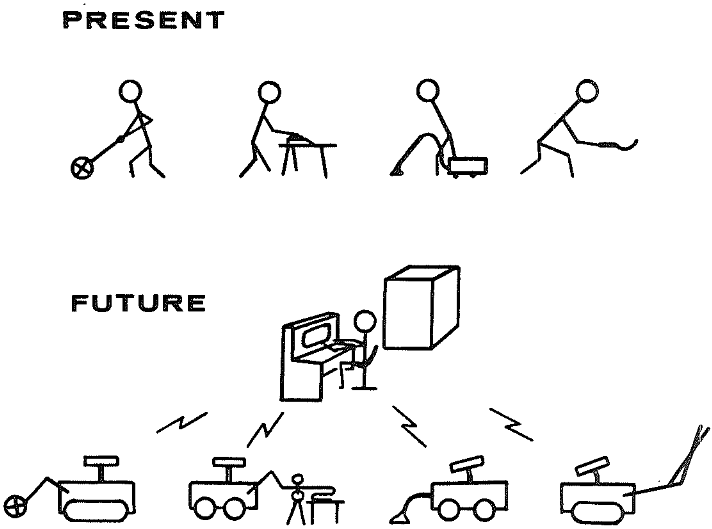
This assumes a reasonably complex task. On the other hand, if the job is so simple that the human telesupervisor's attention is seldom required, then the computer-controller system may not be needed at all. A local self-programmed "robot," as in the case of a washing machine, may suffice. Another way of saying this is that the average interval between manual interventions at the remote work terminal has gone to infinity. In this case,

for example, infinity is equivalent to the average annual calls of the appliance repairman.

What the FJCC panel considered, therefore, are intermediate tasks between these extremes. In this range, the tradeoff situation appears to be depicted in figure 39. Here we have plotted the unscaled coordinates of the average time between communications to and from the remote work terminal and the central system, and the number of work terminals tied to one system. The solid curves give a range of increasing interval required as the number of remote work terminals increases. This follows from the fact that a request from a remote work terminal takes time to answer. Generally speaking, the computer gives the quicker answer. A man may have to go "on-line" for a few minutes to extricate a work terminal faced with some obstacle. Computer-answered requests are in the nature of updated coordinates or the calculation of some geometrical transformation, requiring only a fraction of a second. In either case, however, as system size increases so does waiting time.

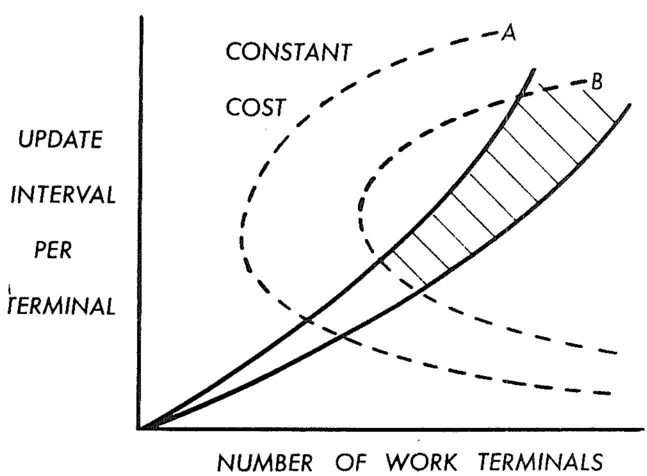
The dotted curves in figure 39 represent constant labor cost functions. Qualitatively, the shape of these functions can be verified by noting that, for example, fixing the update interval but increasing the number of work terminals tied to the system means that system fixed costs are being shared by more tasks, hence the cost per task goes down. On the other hand, fixing the number of work terminals and increasing the update interval may not at first slow down task performance substantially, but share the same tasks over few operators and/or less computer time. Eventually, however, either task performance slows to an uneconomic level, or — as the update interval goes to infinity — the remote terminal must effectively be self-contained and therefore expensive, and cost per task rises again.

The question arises, what do the remote terminals do between intervention or update periods? It has been contended that most tasks under consideration are repetitive in nature and, having established an initial pattern, the human operator can turn control over to the computer for most of the routine remainder. I contend that this is semantic confusion based upon the word "repetitive." In engineering this word has a well known meaning; the internal combustion engine is a good example. But to the



CONTROL OF TOOLS

FIGURE 38



SYSTEM TRADE-OFFS

FIGURE 39

housewife-gardener-farm laborer, who is constantly washing dishes, making beds, mowing the lawn, etc., it does not mean that the motions involved or the tools or materials employed are repeated each time with any degree of precision approaching that involved in the motions of an engine.

Thus, repetition in detail is absent, and the remote work terminal must cope with this lack of order. It must therefore be capable of sensing a reasonable range of shapes, materials, textures, colors, etc. It was my contention that one of the key sensors must be optical because optical sensing is inherently high resolution and does not disturb the object sensed. It can operate equally well over very close as well as reasonably great distances, and can be compared, for example, with mechanical sensing.

Now if shapes, textures, and colors are to be sensed — or even if objects are to be discriminated from their background — some degree of automatic pattern recognition is called for. This may seem too much to demand of a remote work terminal. Many of us know of the difficulties encountered in trying to apply image recognition to military or space missions. However, the situation under consideration here is much more constrained. Full use can be made of computer models of the environment, computer catalogs of specific objects likely to be found in the environment, calculations of perspectives, lists of a specific object's textural or spectral characteristics, etc. In addition, lighting, perspective, and scale (range) can be changed at will. And, as a last resort, the central operator can always be called in. The question that I particularly addressed myself to, therefore, was: where do we stand in the field of image processing and pattern recognition at present, and to what kind of tasks is this field applicable?

It appeared that you can place these tasks into three categories. One is these tasks that certainly or probably will not require any sort of on-board image-type sensory information. The type of task here would be one in which complete storage of the environment is contained in the computer. For example, reactor disassembly. You already know where everything is and you simply go to it and do the job. In the house or outdoors, it would be applying a tool to a well-defined area.

There is a second class of tasks in which sensory data of a pattern or image type is required, and which is capable of being solved at the present level of technology. Such tasks have to do with the handling of objects which are rigid themselves, but which can occur in any orientation in space. For example, in the house dishes are rigid objects; outdoors there are tools of well-defined shapes. Pattern-recognition technology is up to identifying these by techniques such as template matching, scene analysis, or various other techniques developed by many workers. The objects can even be partially obscured and still be dragged out of a complex environment.

A third type of task appears to be well beyond the state of automatic on-board image processing at present. It is represented by objects which are nonrigid. We currently have no techniques for handling the recognition of things that can occur in great amorphous mass. The best example of this is clothing. In the household, clothing can simply occur in a heap. While human beings do a very nice job of sorting clothes, industry has not yet developed any automatic recognition techniques that appear to be applicable to that kind of task.

We have so far considered primarily the case in which we know the environment pretty well — in the house or outdoors. We already have a well-established map of the environment and can direct the mobile unit or the teleoperator to the work point. But there are a number of tasks that involve finding your way in a relatively unknown environment. You may have a rough map, but you need to locate your way locally around obstacles. This also appears capable of being handled by present techniques in image processing. In particular, there are a number of techniques in mapping that have to do with measuring parallax in stereo pairs. This can be done quite accurately. One can develop, on board with relatively simple equipment, a local range map of the area. You may not be able to tell what an object is, but you can at least tell that there is an object at such-and-such a location sticking up above the general level of the terrain, and that it represents an obstacle.

In connection with range finding by image sensing, I noticed yesterday that Dr. Farr commented on the ability of the eye to see stereo even when questions were raised about whether there was real registration or whether the

images were distorted. I can say the same thing holds true in the electronics field. Stereo can be pulled out of two images that are distorted to a certain extent. A typical example is when you are looking at aerial photos in stereo. The ground, if it is not flat, will appear distorted in one view compared to the other view. Yet you can still see stereo quite readily, and so can electronics.

These are some of the things that came out of the panel discussion. The tasks that were analyzed, the recognition requirements, and the applicable technology are summarized in the accompanying table.

Table 1. — Work Terminal Pattern Recognition Requirements

Tasks	Recognition	Technology
Unmapped Areas	Topology	Mapping
	Texture	Statistical
Errands	Rigid Shapes	Template
	Voice	Spectrogram
Harvesting	Shape/Size	Template
	Spectral Information	Multiband
Clothes Handling	Cloth Texture	Statistical
	Spectral Information	Multiband
	Code Marks	Print Reader
	Amorphous Shape	Unknown
Dish Handling	Rigid Shape	Template
	Clutter	Nontemplate
	Spectral Information	Multiband

It may be of interest to some of you to see the basis for these conclusions. For this purpose I am inserting into the record a summary of the analysis of tasks presented at the FJCC:

1. Housecleaning. Taking this task to mean, say, vacuuming the floor and washing the windows, a first look suggests that sensory feedback requirements are minimal. We can assume the existence of two key subsystems: (a) a computer store of two or three dimensional space models of the areas of interest, and (b) a unit that knows the

location and direction of the remote teleoperator at all times. (These will also be assumed present whenever applicable in all subsequent discussion.) The first is straightforward in principle, but is bound to suffer from the same problems encountered with topographic models or maps, namely, the information to be extracted differs in accuracy requirements, type, method of access, etc., for each different user. The second subsystem can be implemented in a variety of ways; for example, by installation of a permanent grid, as in wire-guided vehicles, or by installation of simple electromagnetic or acoustic stations for obtaining a "fix" on the teleoperator.

Vacuuming can proceed in a methodical fashion to insure complete coverage of the area, while avoiding permanent obstacles, such as built-ins. There will always be a certain number of movable obstacles whose position is not known in advance. It seems proper to label these as "semipermanent" if the pressure sensor on the work terminal determines that the obstacle cannot reasonably be moved. Strategies for handling both these situations in order to reach a desired goal have already been worked out, for example, at Stanford Research Institute. Other clutter on the floor such as papers, books, toys, etc., can probably be handled in either of two ways. One is the present method, namely, the housewife picks up troublesome clutter before beginning the vacuuming operation. A more sophisticated and expensive approach is to allow for some degree of object identification. Here automatic pattern recognition of the types described subsequently might come into play.

Window washing provides a very interesting problem for pattern recognition if dirty spots are to be detected. However, the brute force approach appears more appropriate, namely, simply wash all areas of all windows. With a computer space model of window locations and simple touch feedback, the work terminal can proceed to do its job ignorant of the actual condition of the windows. The central telesupervisor may inspect at completion and order selected repeats. The washing mechanism itself, as well as locomotion and extensor systems — particularly outdoors — pose serious mechanical design problems that are, fortunately, outside the scope of this discussion.

2. Clothes Handling. A variety of tasks involve handling cloth materials: making beds, sorting, pressing, folding, putting away, etc. The cycle starting with the removal

of apparel from storage and ending with its return to storage in clean, folded form can be taken as the predominant example. As far as a remote work terminal is concerned, the cycle begins at the clothes hamper, goes through transport to sorting, washing and drying stations, again through sorting to pressing and folding, and concludes with transport to storage. It is clear that a great deal could be done with a systems approach to this sequence. For example, what is the tradeoff between requiring the remote teleoperator to distinguish Ann's from Torrey's and Gale's dresses mixed up in a heap of tangled wash, and requiring each recipient's garment to be washed separately? There are many others. In any case, it is apparent that we cannot afford to have the central telesupervisor on-line for any substantial period untangling wash or identifying garments, so the remote work terminal is faced with the problem of sensing cloth, color, type of material, possibly reading coded or printed identifiers, and possibly having to possess some "concept" of garment shape for the purpose of pressing, folding, etc.

For some of these purposes automatic pattern recognition techniques based upon the classification of textures of spectral response, combined with mechanical handling and shape detection, could conceivably be appropriate. Texture classification has already been investigated with some success in regard to aerial photo data, and spectral data is being applied to crop classification from remote sensors. Print-reader technology, although expensive at present, is probably up to reading garment labels, if the mechanical handling problem can be solved. Although it may be feasible to computer store adequate descriptions of individual garments, this seems excessively detailed. Probably a few dozen garment types can serve as basic categories for shape classification with exceptions handled by the central telesupervisor.

3. Dish Handling. The same type of cycle occurs in the case of dish handling. Although consideration may be given to automatic food preparation, we can take for discussion purposes a cycle beginning with a table of used dishes and utensils and ending with their storage. The automatic pattern recognition requirements in this case may be taken to center on the identification of dishes and utensils at any location within the field of the table, against a background of clutter and nontarget objects such

as table decorations. Once the target objects have been located in space, their further manipulation through waste removal, washing, drying, and storage appears straightforward.

The automatic pattern recognition problem in this case is greatly simplified for several reasons: (a) the target objects are rigid bodies that can only be visually transformed by the operations of perspective change and scale, (b) they must make contact with the plane of the table or lie on other objects that do, and (c) the shapes are often simply described geometrically, e.g., round plates. In this case it appears that well-known template-machine or scene-analysis techniques can be adapted to the situation. For example, if the work terminal knows its position with respect to the table, then a perspective and scale transformation will tell it the expected shape of any plate of known size at any point on the table. Economical incoherent optical methods, or simple scanning techniques, can then be applied.

4. Gardening. Outdoors the work terminal encounters a more varied terrain, but enjoys two advantages. One is that the tasks generally do not involve the manipulation of complex objects, but rather the application of a specific tool to an area. Another is that outdoors we can probably permit the work terminal to be powered by an internal combustion engine, freeing it from the limits of batteries or the constraints of cables.

5. Unmapped Operations. Occasionally the suburbanite is called upon to clear an area of brush, rocks, etc., but more often this task arises in rural areas and forestry. It is a task worth brief consideration. The problem is that no map exists on the same level of detail as that of the yard or house interior. Furthermore, we cannot afford to have the central telesupervisor driving the vehicle on line except in emergencies. Thus, the remote work terminal must be capable of developing a local map as it goes along.

Techniques for doing precisely this in connection with planetary rovers have already been investigated, for example, by Sutro at M.I.T. They are based upon optical ranging and photogrammetric reconstruction of the sensed data. They probably need to be augmented by a modest

degree of texture classification to discriminate, for example, between bushes and rocks, so that the former can be cut down and the latter avoided.

6. Errands. Many errands need to be run within the premises of any household, both indoors and out. The particular type chosen for consideration here is that characterized by the request: "Fetch the screwdriver." With this type of task we have just introduced for the first time a new mode of system behavior. Namely, not only must the work terminal be under central telesupervisor control, it must also, to some extent, be under local customer control.

It is clear that this requirement exists implicitly throughout the list of foregoing tasks. For example, all work terminals should be able to respond to the local voice command, stop, by freezing all motion. Touch commands (including a stop button) should also be present. It is probably desirable in some situations to have the customer "program in" a complex sequence of motions by guiding the work terminal through them manually. Automatic voice recognition of the numerals and a few words, across a wide spectrum of speakers, does not appear to be beyond the present state of the art.

In any case, it does not appear unreasonable to expect the work terminal to respond to simple verbal requests, perhaps initially given in some agreed-upon code form. In the case of fetching a tool, presumably a catalog of individual items or tool class characteristics can be computer stored. The pattern recognition problem for those cases where the specified tool is not in its usual storage location, but must be searched for within a given area, is similar to that of the dinner dishes. The objects are rigid, of well-defined shape, and must obey gravity.

7. Agriculture. The harvesting of fruits and vegetables is a tedious job. It is not at all clear, however, what, if any, role the remote work terminal might play in the future of agriculture, because a number of mass production methods under investigation may prove difficult to compete with. Machines tailored to specific crops are presently in commercial use or under development for such crops as lettuce, asparagus, tomatoes, and grapes. Much of this work is going on at the University of California at Davis, in conjunction with related work in plant

biology. The objectives of the biological work are to develop fruit and vegetables that are more suitable for the mechanized methods of harvesting; for example, by forcing most of the crop to develop simultaneously, or by making the fruit more resistant to bruises, or by making the stem more easily detachable from the branch.

These approaches have not met with universal acceptance. For example, although a strain of tomatoes has been developed in which 80% of the crop matures simultaneously, manual removal of green or bruised tomatoes still is required. The harvester simply cuts the stems, separates vine and tomatoes by shaking, and discards the vine. Unfortunately, this variety of tomatoes was developed in California and is not suited to growing conditions in most other states.

Similar conditions hold for machine harvesting of tree fruits. So far all the successful methods have depended upon shaking the tree mechanically. However, clamping onto and shaking a tree can result in bark injury and subsequent infection. Also, catching the falling fruit in a large frame or basket without bruising it can prove difficult.

Thus, there still exists an opening for either low-cost work terminals to do individual fruit picking, or at least for operator-controlled work terminals to help set up and operate the mass production methods. In pattern recognition, the task can range from relatively simple (as when spectral information together with range and size can be used to identify ripe fruit) to very difficult (as when the discrimination required is that of a green object against a green background, often in the shade). Nevertheless, it is relatively easy to conceive of a computer-guided work terminal successively stationed at several points around a tree, a rough computer volume model of the tree, and successive sensory views, each of which covers some portion of the total tree volume. If fruit meeting the specified criteria is found, locations can be noted and picking arms positioned while the sensor goes on to the next volume. Mechanical speed and economy are obviously crucial.

In conclusion, it appears that the known technology in the field of pattern recognition is up to most of these tasks, with the exception of apparel recognition under wet-

dry-tangled conditions. The main engineering problem will be economics. Historically, automatic image recognition technology has developed around a set of military space problems with very special characteristics. Among these characteristics are: (a) computer-stored prior information about the sensed data not available to the pattern recognition system, (b) few constraints except the laws of physics operating in a complex natural environment to limit what can appear in the sensor's field of view, (c) pre-coding of natural phenomena excluded in any except complex ways, and (d) severe speed and accuracy requirements. Along with these characteristics has generally gone an acceptance of relatively expensive systems.

In the case of remotely performed domestic, agricultural, or other labor shortage tasks these constraints are substantially relaxed: (a) the time-shared computer is already present in the system, (b) the environment is relatively limited and well-cataloged, (c) the coding or lettering can be freely placed at critical points if this is helpful, and (d) speed requirements are modest (with the possible exception of crop harvesting) while the central telesupervisor is always on hand to intervene in case of difficulty.

CHAIRMAN JOHNSEN: Thank you very much. The next speaker is Art Critchlow, who is involved in commercial operations of this nature.

MR. ARTHUR J. CRITCHLOW, Mobility Systems, Inc: As Mr. Hawkins mentioned, we discussed some of these same things at the FJCC. I would like to digress a bit, however, and talk about computer-controlled vehicles and explain what we are doing that may be of interest to you.

Mobility Systems is a commercial outfit, and as far as we know, we are the only company making a living on computer-controlled mobile vehicles. Since it is a commercial application, we have to be cost competitive with labor in the field. We have to provide something to our customers that will do a job for them reliably, accurately, and on schedule. So we have had to develop mobile vehicles, and our approach here has been to use the computer to do those things it does best and let a man do those things that a man does best.

Basically, the computer has a very good memory and an equally good analytical ability. It can remember what to do and in what sequence to perform certain tasks,

but it has poor pattern recognition capability, and a manipulator of any kind doesn't have the same dexterity as a man. So one of our first applications has been to make vehicles which will carry a man to the task and tell him what to do, and let the man do the pattern recognition and perform the actions requiring dexterity.

Our next step is to take a vehicle with an arm to the picking location. We have made a picking arm which will handle defined objects such as boxes for garments or shoes, or cases of groceries. If you can describe the object in some good geometric terms and tell us where it is located, we can find it and pick it up, if it is not too heavy.

CHAIRMAN JOHNSEN: Computers are expensive.

MR. CRITCHLOW: Today this is no longer the case. We are currently buying computers for less than $5000 for our control work. Not only are they inexpensive but they are going down all the time.

We have a disk file; these are also fairly expensive. In this file we store all the information about the warehouse. It has the description of the warehouse; it knows where every shelf is, where every aisle is, where every item in the warehouse is located. It knows the inventory in the warehouse by quality, size, weight, location, vendor, order, anything you need to know. It also contains information about the orders in the warehouse. So we tie all this together and provide complete integrated data processing and a details-handling system. To do that, we come out to what we call the warehouse control unit, which is a little auxiliary computer of a type I will show you in the movie here. Basically, however, this control unit goes to wires in the floor of the warehouse, forming a grid pattern, and this grid can be as fine as required, so you can take any path through the warehouse. In particular, the computer can provide the best path for a given function.

Since the time is short, may we run that first movie? This is our prototype computer-controlled vehicle (fig. 40). As you can see, it makes turns and takes any path through the warehouse. This is what we call a drive module. It can have as many types of secondary modules attached to it as desired depending on the function you wish to perform. The black tape on the floor is covering

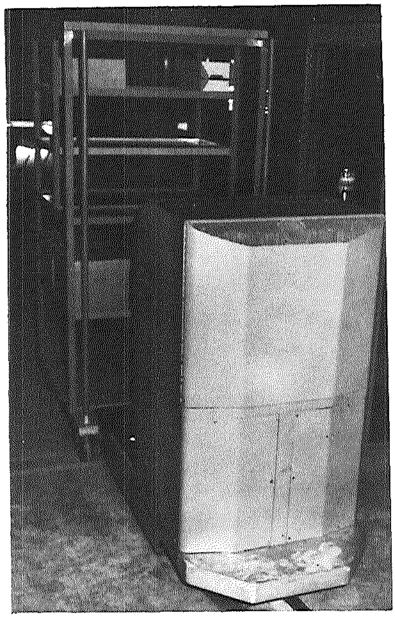


FIGURE 40

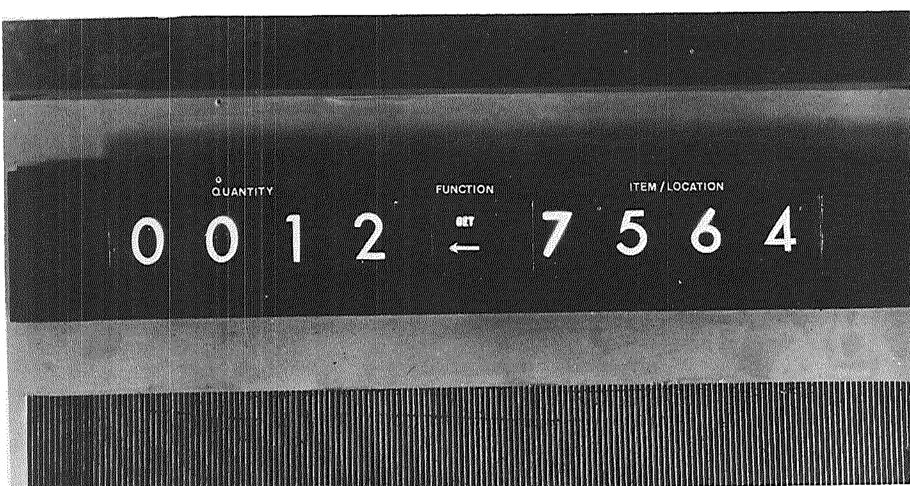


FIGURE 41

some wires which are used for guidance. They have a radio frequency current in them which is picked up by an electromagnetic sensor on the vehicle. The sensor is mounted on a shaft that sticks out in front of the vehicle. That shaft is attached to the steering wheel, which is servo-controlled. You can see the sensor arm following the black line there. One of the problems in this kind of system is that safety is absolutely essential. So we put safety devices on top of safety devices. Note that the technician rides backward and he doesn't have to hold on to the vehicle with the new versions, but he can work as he goes.

A display tells the order picker what to do. He is told to pick 12 items at location 7564 (fig. 41). Quantity 12, location 7564, and he is putting those in his module. Since he is carried to the right location and told what to do, he can actually work about three times as fast as a man could in the old scheme of pushing a cart around the warehouse.

MR. FLATAU: Does he stop the vehicle, or does the computer stop it?

MR. CRITCHLOW: The computer does.

QUESTION: How does the computer keep track of the cart?

MR. CRITCHLOW: Marks on the floors are optically picked up. There is a wheel counter on each wheel, which counts rotations. There is two-way communication from the vehicle to the computer and back. So the vehicle is constantly transmitting its location back to the computer. This, of course, is stored in the disk file or the core memory of the computer. We also have some safety devices on these vehicles. One of these is a safety transmitter, which is not on this prototype.

The order picker is told to pick seven items and presses the "Task Complete" button. The Task Complete is an all-purpose button; it just says, "You told me to do something, I have done it." The computer remembers what it told him to do, so it marks that task as completed.

QUESTION: Do you have such a system now that is being used commercially?

MR. CRITCHLOW: Right now we have two of what we call our "local control" systems, which use the same type of vehicle, but it is not yet connected directly to the computer.

We also have in test and production our first full computer-controlled system. Both systems use the same vehicles controlled in the same way, except that the two-way communication link to the computer is not operated. Instead, in those systems the man sets a number of control dials to enter a location. Dial settings provide an aisle number, a bin number, and a height. He then pushes a "Go" button and that stores all this information in the local memory of the vehicle.

MR. FLATAU: Would you briefly describe the two-way communication link?

MR. CRITCHLOW: Essentially it's an antenna in the floor, except it has to be balanced in such a way it does not radiate too much.

MR. FLATAU: What kind of communication mode do you use?

MR. CRITCHLOW: Just a parallel transmission line.

MR. FLATAU: Could you say anything about the required bandwidth?

MR. CRITCHLOW: We designed this one for a bandwidth of 20,000 bits per second, or roughly 50 kc bandwidths, and we could get more if we needed to.

MR. FLATAU: Is that enough, or do you have room to spare?

MR. CRITCHLOW: We have more than enough. In fact, we started out with the idea that we would use thirty vehicles and each of them would have not only computer control but a computer-controlled arm on it, also. Since these vehicles don't have arms on them, it takes less data transmission. We have more than enough. It turns out, also, we are putting more computer power in the vehicle itself. Our communication problem is trivial.

MR. FLATAU: What kind of parameters do you need to run the computer?

MR. CRITCHLOW: The installation I am showing was run off of what is called the Allen-Babcock system, a remote time-sharing system. The computer is an IBM 360-50. It is run over a telephone line, which has an effective bandwidth of

2400 bits per second, but actually we are getting about 1200 bits per second on our time-shared terminal. Each vehicle requires about 15 bits per second to run in full computer control.

One of the things I started to mention was the safety transmission on some of the new vehicles. This transmits an electromagnetic field about 20 feet in circumference. When two vehicles detect each other they stop and wait for operators to take control. These are standard printed circuit cards. We use integrated circuits and back-panel wiring. Quite a bit of computing power is used in the control unit that rides with the vehicle. In addition, there is a warehouse control unit which, in this case, is just a local interface with a communication line interface in it — an rf transmitter and receiver. There is also the tie-in to the remote computer. We are transmitting through the remote computer to the registers, and actually storing command information in the vehicle.

One of the things I want to show you is the computer-controlled arm. This is a true teleoperator because right now it is being operated in this picture by two of our engineers, and you will notice that they are not overlapping functions. But it does show that you can pick up boxes with a vacuum grabber and slide the box on to a shelf. This arm is performing the function of picking garment boxes in a warehouse and putting them on the shelves on a vehicle. It works quite well.

The same arm has been modified slightly to pick up shoe boxes, and we have put it on full computer control. Some of the attendees here came down to see this arm operate while they were at the FJCC. The arm works under full computer control with overlapped operations, in X, Y, Z, and rotation movements. Ray Goertz was making some comments about the overlapping operations that a master-slave unit can perform. This arm can overlap also, but the particular device shown in the movie did not overlap operations except in a computer-controlled version. The movie was made about a year and a half ago. Shown are two engineers flipping switches. It is really a chore to flip all the switches in the right sequence, but the computer finds it very easy to do. That is about all we need of the movie, so you can stop it if you want to.

DR. MURPHY: Is there something noted when it is the top box?

MR. CRITCHLOW: The computer keeps track, in the disk memory, of the location of every box — there are five, six,

or ten boxes in a stack. In fact, we worked out ways to keep track of a pallet pattern of bases stacked on pallets in warehouses.

Again, these are completely flexible programs. They can operate on any size box, any size warehouse, so that all you have to do is store in the computer a description of the warehouse and the size of the boxes, and the programs will take it from there and adjust the movements to match.

I have some slides to run through quickly, which will give you an idea of what one of our actual commercial installations looks like. Here is the control panel (fig. 42) for what is called the local mode of operation. The two top dials are labeled 1 to 10 and use that as an aisle address. The next two are labeled 1 to 10 also, to set the bin address on the bottom of the list.

In the next slide (fig. 43) is one of our vehicles standing in the aisle with a man operating it under local control. This is a production vehicle. You see a couple of the safety features on top. The little box there is a safety transmitter I told you about.

The operation is rather interesting to watch because the safety transmitters on the two vehicles will talk to each other, and if they come within 15 feet the vehicles automatically slow down; if they come within five feet, they automatically stop. Some of the workers have phenomenal faith in these vehicles, because they will walk between two of them separated only by these safety transmitters. I wouldn't do it.

We also have a vehicle which is either man-controlled or computer-controlled. It is a side-lift or side-loading fork truck and it can carry two pallets full of parts. This can be used, of course, for carrying any kind of object that is on a pallet or boxes where you can note its location. We have sold some as an unmanned, computer-controlled vehicle. It will reach out and pick up a loaded pallet of something and take it somewhere in the warehouse and put it away or retrieve something from a rack and take it to the shipping dock.

The lift order-picker vehicle you see here is being operated at high altitude in the warehouse, and there's a girl riding (fig. 44). This woman found it very comfortable

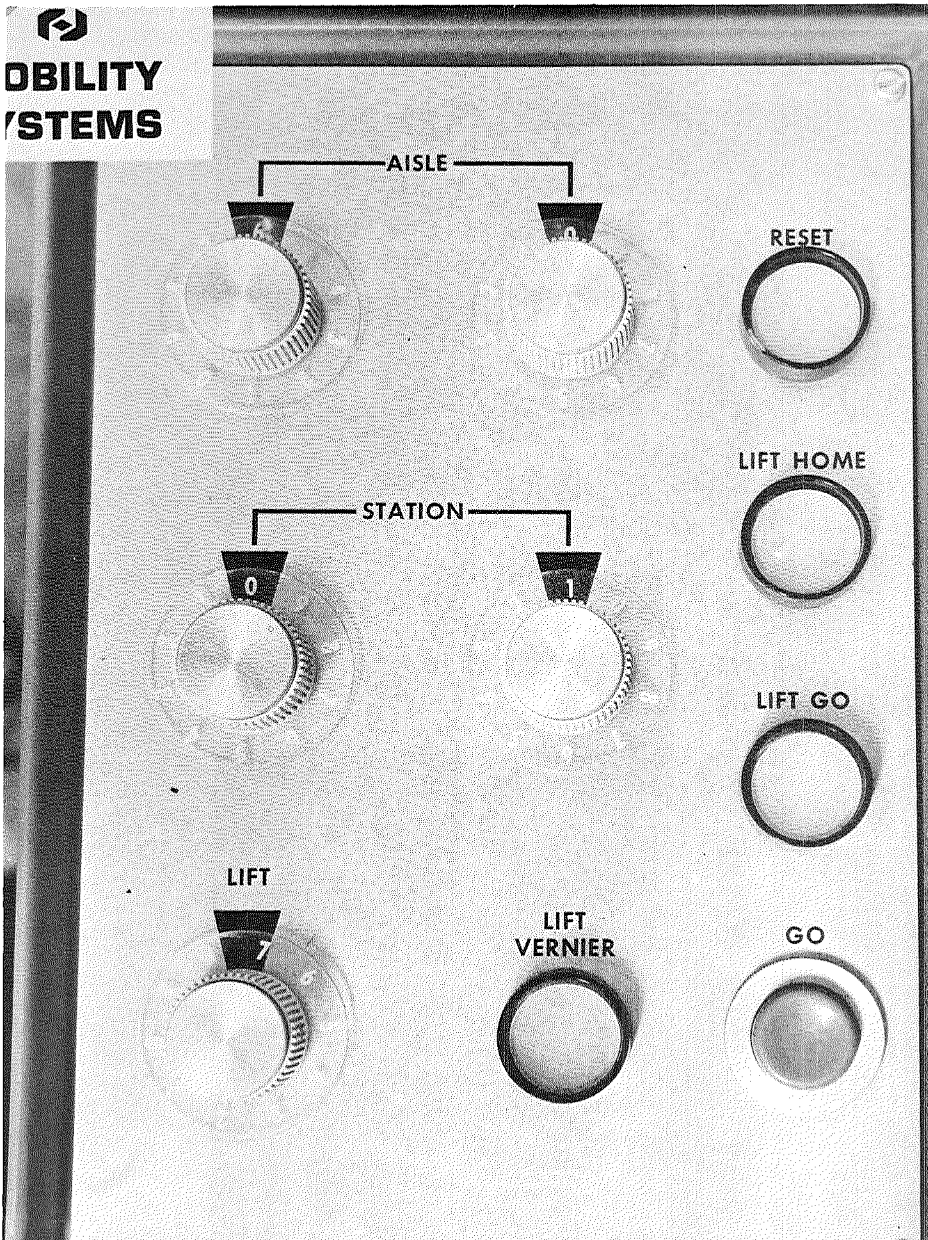

OBILITY
YSTEMS
AISLE
RESET
LIFT HOME
STATION
0
1
LIFT GO
LIFT
7
LIFT
VERNIER
GO

FIGURE 42

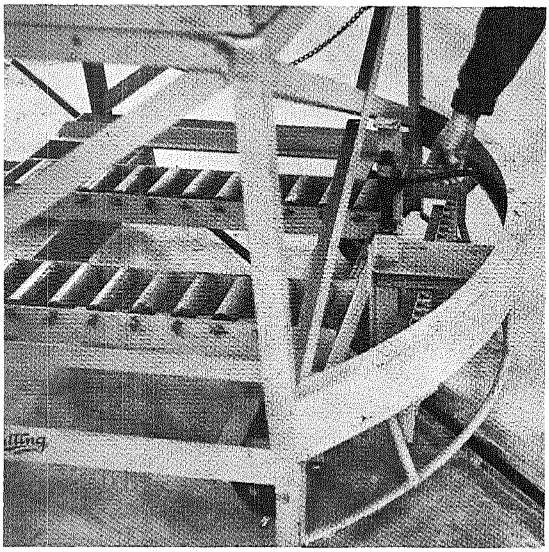


FIGURE 43

FIGURE 44

up there to operate the vehicle, and pick. One of the things we sell to customers is space-saving. You can use very narrow aisles to go high, and that helps to pay for the system.

Our lift system is unique and patentable. A servo-controlled motor runs the hydraulic lift and gives us smooth, precise control. We can draw a pencil line on the lift, for example, and repeat, — go down to the bottom and come back up — and line up with the pencil line again within five-to ten-thousandths of an inch, at least one or two times in a row. At the bottom of figure 45 you see the power panels for this vehicle. We use all power transistors in a bridge circuit. There are just 25 or 30 or 50 power transistors in parallel. It turns out to be the cheapest way to do this within the scope of our problem.

When we talked to the FJCC, the subject was "Human Augmentation by Computers and Teleoperators." Take the idea Joe Hawkins mentioned: we can use a computer to control a number of teleoperators remotely and have a human supervisor override. Well, we coined the name telesupervisor for the man who controls the remote teleoperators. And, incidentally, there are some new techniques coming up in microwave communications that seem to offer more bandwidth, so we may be able to use actual broadband television within a local area. This is considered to be something within a 10- or 20-mile radius of the central.

In this slide (fig. 46) we are concerned with a system that is an economic problem. There are 100 computers in a hundred locations in the country. There are exoskeletons on the man, sensors, displays, and teleoperator controls — 20,000 sets of these. In other words, 200 for every control computer. We figure that 20,000 telesupervisors, each controlling five teleoperators on the average, can run 100,000 teleoperators at remote terminals. This is planned as a two-arm, 50-pound capacity teleoperator with a vidicon scanner and a chance of two legs or dual tracks to do economic useful work in either a domestic situation or some other unpleasant environment where people aren't willing to work.

In the next slide (fig. 47) I worked out roughly what it would cost to fully develop this kind of system. It will be interesting to check these numbers against your own experience. System planning, engineering programming, hardware,

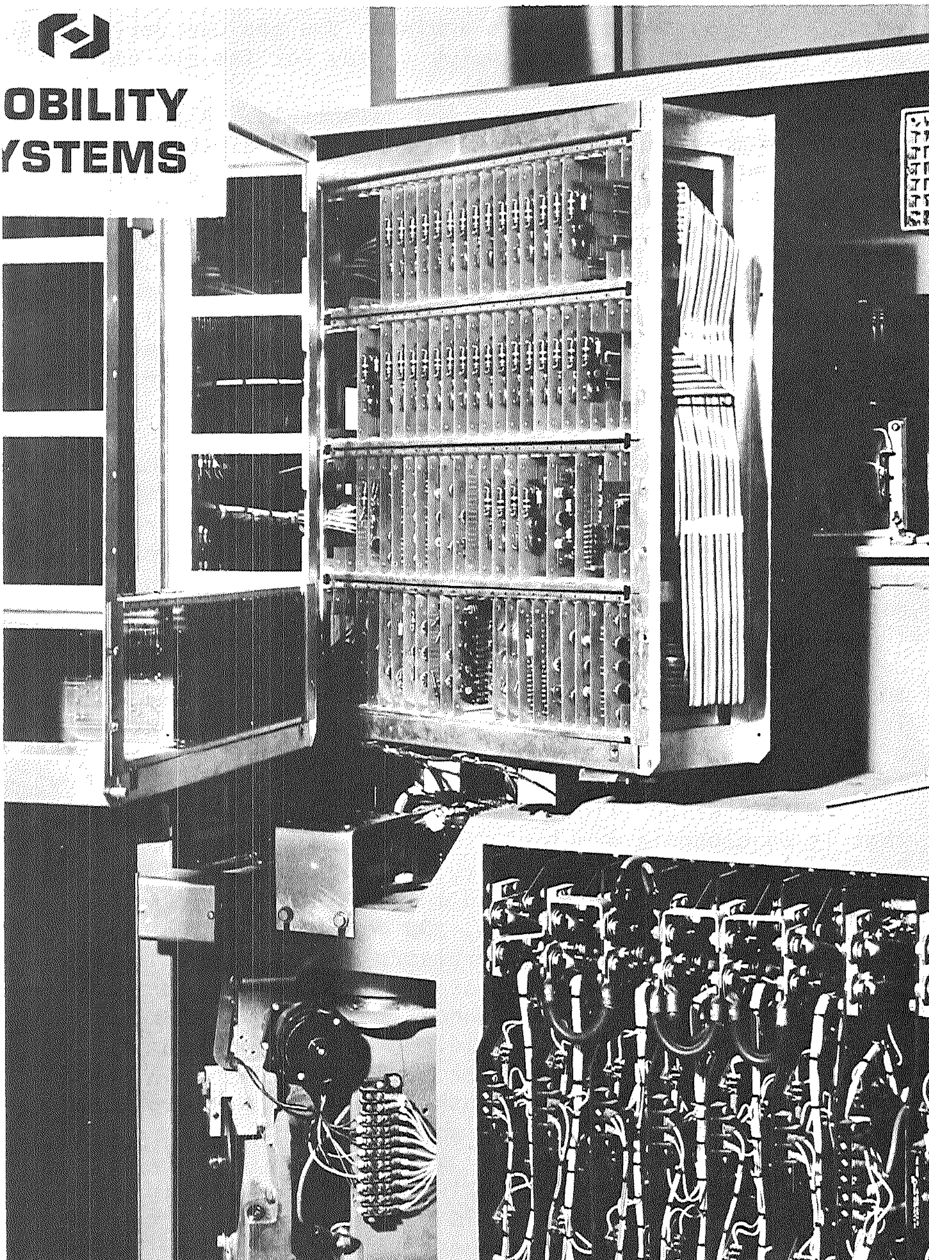


FIGURE 45

SYSTEM CONFIGURATION

	Required
Control computers and peripheral equipment	100
Telesupervisor controls exoskeleton, sensors, displays and controls	20,000 sets
Communication – Average length 10 miles, 1 megahertz bandwidth	20,000 paths
Teleoperators (Work terminals) Two arms, 50 lb. capacity Vidicon scanner Two legs or dual tracks	100,000

FIGURE 46

SYSTEM DEVELOPMENT PROGRAM

System Planning	$1,000,000
Engineering	2,000,000
Programming	2,000,000
Hardware Test	800,000
System Test	400,000
	$6,200,000

FIGURE 47

and system test. This is the development only. The numbers come out around six to ten million dollars, in that order of magnitude. It turns out not to be very important in the total scheme of things.

The yearly cost of operation is shown in this slide (fig. 48). We have to pay the telesupervisor operators about \$3.00 an hour on today's scale, plus supervision. Twenty thousand teleoperators would cost \$50 million; building and facilities, \$12 million; administrative and miscellaneous, \$50 million. So this whole system would come to \$690 million, which is something maybe only the government can afford, but this is being approached as though it were a viable business venture. By the way, the idea is based on a theory of availability in 1975; not necessarily today. It will take that long to develop it and to solve the social and political problems.

Then the income for 100,000 teleoperators at \$2.00 an hour on the prime shift or \$1.75 for the second shift works out to be \$774 million per year, so the yearly income is greater than the outgo (fig. 49). So you get a net income of \$84 million a year — not a very good return on the initial investment by industrial standards, but significant from a social viewpoint (fig. 50). You are finding work for 100,000 people per system, providing functions that are not otherwise available, and doing jobs that are not otherwise being done. The approximate total system cost is shown on this slide (fig. 51).

CHAIRMAN JOHNSEN: Any questions?

COMMENT: In one of those slides you showed very narrow aisles, and it looked like there wasn't much clearance between the vehicles and the racks.

MR. CRITCHLOW: Five inches on each side.

MR. BURGESS: Was that guided?

MR. CRITCHLOW: This was guided on the floor, but not by track. We put specifications on the floor level, but have had no trouble with contact. We are guiding with an accuracy which is hard to measure. Something like an eighth of an inch or less.

YEARLY COST OF OPERATION

1. Telesupervisor Operators	\$525 million
2. Supervision – 19%	53 million
3. Maintenance of Equipment	50 million
4. Building and Facilities	12 million
5. Administrative and Miscellaneous	50 million
Total	\$690 million

FIGURE 48

SYSTEM INCOME

100,000 Teleoperators

80% utilization on prime shift at \$2/hour

60% utilization on second shift at \$1.75/hour

Total per day = \$21.20 per Teleoperator

\$100,000 × \$21.20 = \$2.12 million/day

365 days × 2.12 million = \$774 million per year

FIGURE 49

SYSTEM PAYOFF

Net Income \$774 − 690 = \$84 million/year

Return on investment is low by industrial standards.

FIGURE 50

CAPITAL INVESTMENT

IN 1975 (1968 Equivalent)

Control Computer Complex \$750,000 × 100	\$ 75 million
Telesupervisor Controls \$5,000 each × 20,000	100 million
Communications – \$2,000 per channel × 100,000	40 million
Teleoperators \$4,000 each × 100,000	400 million
Total	\$615 million

FIGURE 51

QUESTION: Would it be possible that you could save the guidance system by using tracks where the vehicle would just slide out, then move over and engage another track in the next aisle in a building area where space was that close?

MR. CRITCHLOW: You could. In fact, that is commonly done in the forklift truck business, and the advantage of this method is the flexibility of guiding out an aisle, around a curve, and guiding into another aisle. Also, the cost of the steel guide rails along the side is quite expensive. We are talking here about roughly 5000 feet of track, so you have to install a guide rail on each side, that is 10,000 feet. By the time you get through with that, it is cheaper to put guidance on the vehicle.

MR. FLATAU: Could you say something about the cost of such a vehicle?

MR. CRITCHLOW: Yes, they are in production and they range from thirty to fifty thousand dollars, depending on the type of vehicle. That is just the vehicles alone. In addition, the system costs are running about three and a half to four and a half dollars installed per foot of aisle.

MR. FLATAU: Does that include your communications link?

MR. CRITCHLOW: The vehicle includes all communications and the control, complete and ready to operate. In addition, there is a programming cost, which is a one-time charge, and that is pretty simple if all you want to do is guide the vehicles; but it turns out that everybody wants this also for order processing, inventory control, and other data-processing functions which are hard to separate.

MR. FLATAU: Two more questions. One of them: what is the power source of the vehicle, a battery?

MR. CRITCHLOW: Battery, 550 ampere-hour, 24 volts, lead-acid.

MR. FLATAU: What other anti-collision device do you have? I don't mean vehicle to vehicle, I mean vehicle with objects which the people have left around by mistake.

MR. CRITCHLOW: On these vehicles there's no collision device. We have a safety bumper that will stop the vehicle if it bumps into something, and we are thinking very

seriously of putting on a sonar device which will detect objects. We haven't had that kind of trouble. If the vehicle loses a guide signal for any reason, it will automatically stop.

CHAIRMAN JOHNSEN: One more question.

QUESTION: You mentioned earlier in your presentation that there was something like a three-to-one efficiency ratio in favor of your computer control over man's control. Were these figures arrived at in some systematic fashion? It seems to me a man who is reasonably well trained and of average intelligence could very easily learn a cataloging system. With well-marked aisles and shelves, I don't see how you can really obtain anything like a three-to-one difference.

MR. CRITCHLOW: I compared the man riding one of our computer-controlled vehicles to the man pushing a cart, which is what was being done before in these warehouses. A man pushing a cart can walk about one foot per second and has to carry a piece of paper with him. He has to look at the piece of paper, recognize something on it, look around, find the object, and quite often climb up or reach up to get it. In fact, in some of these warehouses they actually had portable ladders for the man to use. He has to check off the item on the list and then pick up the object. This analysis was done on a time-and-motion-study basis. We actually can achieve three times the output.

QUESTION: If you had a machine that a man could ride, with an elevator, what ratio would you have?

MR. CRITCHLOW: Then the ratio is only about two to one. There are on the market what are called "Order Pickers," vehicles that a man does ride. In that case the man has to control the vehicle, and while he is controlling the vehicle he can't do anything else. In our system he can pick and pack, tag, wrap, and do other functions as he is riding, because he doesn't have to control the vehicle. This is based not only on very careful analysis by us, but analysis by the best industrial engineers in the country.

CHAIRMAN JOHNSEN: One more question.

QUESTION: I was interested in the five thousand dollar computer. Is this the computer you use with the disk system?

MR. CRITCHLOW: I am talking really about the warehouse-control type of computer.

COMMENT: The $5000 is for the warehouse control unit, but you have a lot more money in the computer.

MR. CRITCHLOW: This is the data processing computer, I should perhaps have mentioned. All we do for the data processing computer is hook onto the existing computer and get information from it on a periodic basis.

CHAIRMAN JOHNSEN: This is the one in Palo Alto.

MR. CRITCHLOW: Yes. It is an IBM 360 Model 30 or 40, or 50. It is time-shared, so we use a fraction of its time, or two percent perhaps. All we do is transmit data from here to the local warehouse control unit, and then the computer is free to go about doing anything else it wants to do.

CHAIRMAN JOHNSEN: Thank you very much, Mr. Critchlow.

MR. MAGEE: I want to remind you we are starting at 8:30 tomorrow morning.

(At 5:20 p.m. the conference was recessed until 8:30 a.m., Thursday, February 27, 1969.)

THE SECOND DAY OF COLLOQUIUM

The 1969 Colloquium on Advancements in Teleoperator Systems resumed at 8:30 a.m., Thursday, February 27, 1969, with Edwin G. Johnsen presiding.

CHAIRMAN JOHNSEN: We will start with teleoperator systems. Most of the next group of speakers will probably have only brief comments to make about what they are doing. I would like to start with Mr. Swain, and have him give a brief rundown of what they are up to. Actually, this isn't quite a system that he has, but we will put it in that category anyway.

MR. ROBERT SWAIN, Aerojet-General Corporation: Mr. Johnsen asked me to tell you about one of the tools Aerojet is developing for use by the astronauts. We developed the tool for use by the astronauts from one of the tools we had originally designed and developed for use by a manipulator in the disassembly of the NERVA reactor. Disassembly of the NERVA reactors requires that the forward closure of the pressure vessel be removed. This is held in place by 75 5/8-inch bolts and each bolt may take a thousand foot-pounds of torque to break it loose.

We started out with an impact wrench and a manipulator, and went around the forward closure and unscrewed each bolt. We then used the manipulator to pick up the bolts and deposit them in a container. The vibration of the last few bolts had reset the other bolts and they were no longer loose. It was apparent that we had to develop a tool that would hold on to the bolt, so that when the tool removed the bolt it would grasp it and subsequently deposit it in the container. We also found that if you hold a tool with a manipulator, you have to raise the tool as the bolt comes out, and this is difficult to do at the proper rate. Thus, as we developed the tool, we expanded the design so that the bolt was essentially swallowed up into the tool. With this design, the manipulator did not have to move as you removed the bolt.

During a visit to the Marshall Space Flight Center (MSFS), while showing them the type of tools we could develop, we discovered that they had a problem. The S4B tank, in order to be used as a space workshop, required that the astronaut first take off a hatch fastened down by 75 5/16-inch bolts. MSFC had conducted a study in their neutral-buoyancy tanks to determine how long it would take a man to remove these bolts with conventional tools. They ran into the same problems we did. The natural-buoyancy diver — the astronaut — free to drift in space, drifted away, and he couldn't maintain himself in position. Also, he didn't know what to do with the bolt when he got it out because, wearing an astronaut's glove, he could hardly pick up a 5/16-inch bolt. When MSFC saw our tool they decided that it was exactly what they needed and asked if we could develop one specifically for removing the bolts from the hatch. This we did with no problem except that it was a space design and yet had to be tested at 50-foot water depth. Our difficulty was sealing it so that it would work under water. The diver using this tool, while completely free-floating in water, was able to take out these 75 bolts in 16 minutes compared with over two hours using conventional tools. The added feature in time-saving was that when the tool grabbed onto the bolt the operator needed no more restraint; he did not have to fight his own body to stay in position.

It so happened at that time that the hatch design was changed and the requirement for bolt removal was eliminated. The decision was made to go ahead with the space station work and we were asked to design a tool that, in addition to taking the bolts off, would install them. They were interested in 1/4-, 5/16-, 3/8-, 7/16-, and 1/2-inch bolts and wanted the installation torque controlled. NASA has a requirement that all bolts are set with a certain torque, so we have developed this tool accordingly. It has been successfully bench-tested, and it will, indeed, take any size bolt and install it to proper torque. The tool is designed to hold onto the bolt so the operator only needs one hand. He can pick up the bolt with the tool, run it in, go back, and get another bolt; or he can take the bolt off and put it into a container.

I agreed with Mr. Johnsen that I would lead a discussion, but I didn't know until I got here that I was going to make a speech. This slide (fig. 1) shows a bolt-removal tool sealed for underwater testing, and the unit redesigned for bolt installation (not sealed for underwater testing). The basic tool has been written up as spin-off technology for possible commercial application.

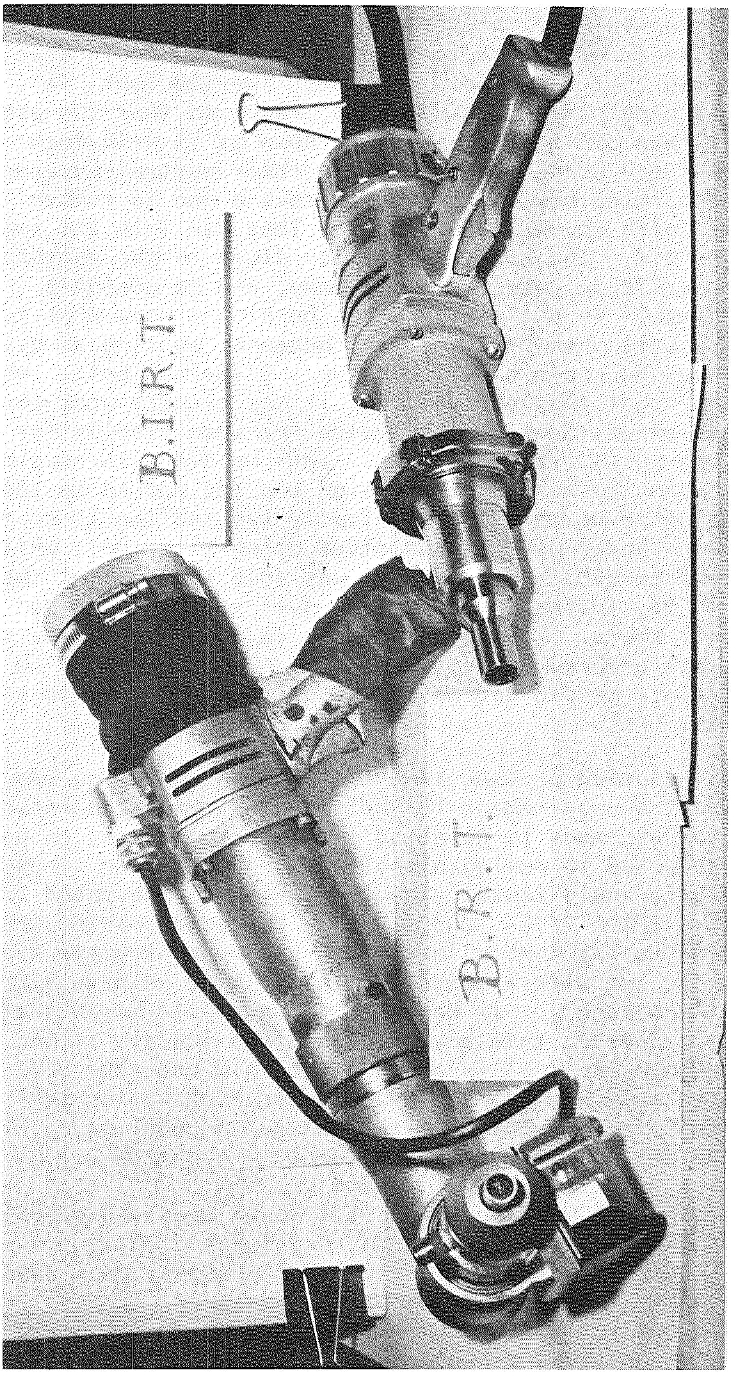


FIGURE 1.

CHAIRMAN JOHNSEN: When you install it, how do you keep from ruining your threads?

MR. SWAIN: We worried about that, but there is no problem. We wondered how we were going to be sure we were vertical or horizontal at least true to the axis; and since we are now using a man to feel, you just take the bolts and put them in. The easiest way to put a bolt in accurately and fast is not to look at it. You are talking about hand dexterity, and if you watch you can get confused.

QUESTION: What is the smallest bolt you have successfully installed?

MR. SWAIN: Five-sixteenths.

MR. FLATAU: Not a number four or something like that?

MR. SWAIN: No, we don't go that small. In fact, I really don't think they will go to a half-inch in space, but we are developing the tool for it.

QUESTION: What is the mechanism for holding the bolt?

MR. SWAIN: It is a combination mechanism. We use a special 12-point socket and it has a hole in the head. As the tool retracts, a collar expands into the hole and holds it by friction.

QUESTION: Where does the counter-torque come from?

MR. SWAIN: It is an impact wrench, so there is no counter-torque. There is a two percent residual torque. If you are installing with 100 ft-lb, then you are going to feel roughly 2 ft-lb. We did find out that you had to use an impact wrench. Astronauts do have to be restrained, and two percent is really no problem.

CHAIRMAN JOHNSEN: Thank you very much, Mr. Swain. I would like to ask Dr. Chesley now if he could tell us what his company has been doing recently.

DR. FRANK G. CHESLEY, Central Research Laboratory: Thank you, Mr. Johnsen. I would like to express my appreciation for being invited to this meeting and for the opportunity to say a few words about the activities at our company. It is very exciting to learn of the developments in orthotics and pros-

thetics that have been described and to hear the remarks of Colonel Brown regarding the hand. The efforts in our company have principally been directed toward developing and producing a variety of master-slave manipulators which are mechanically coupled. These devices permit manipulations to be carried out in hostile environments; unfortunately, in most cases, they are inefficient and unsatisfactory when compared to the case with which we use our hands. Most of the manipulators which we have produced are used for handling radio-active materials or devices. A relatively small number have been supplied for handling hazardous chemicals and high-energy fuel. In a typical installation the manipulators are usually located at fixed work stations and pass through shielding walls which vary from several inches up to five or six feet in thickness.

One of the projects on which we are working is an electro-pneumatic servo system controlled by dc potentiometers. This system was originated by the Northrop Corporation and we are continuing development under a license arrangement with them. The system is not a true force-reflecting type, but it does provide a sense of feel by means of a simulated force reflection. You see here the prototype system (fig. 2). As the operator's finger bends, electrical resistances of the glove potentiometers alter. A bridge circuit detects the change and uses the error signal to control pneumatic actuators in the slave hand. A pneumatic bladder under the operator's forefinger creates a pressure that gives him a sense of touch. If the slave hand is stopped by a solid object, it cannot reduce the glove signal to zero, and the bladder pressure under the operator's finger increases as the operator curls his finger further. The mechanical system consists of miniature drive chains, sprockets, and return springs. Pneumatic controls are actuated through torque motors driving proportioning valves. Further development will include loops driving wrist, elbow, and shoulder movements to achieve an articulated arm.

Argonne National Laboratory was principally responsible for originating the earlier model of master-slave manipulators. At Central Research Laboratory we are making about 11 such models. These devices have evolved into this multiplicity because the requirements and the tasks performed have become more specialized. The sealed master-slave manipulator has now been highly refined and provides sensitive manipulation with reasonable load handling capacity inside shielded enclosures demanding ultimate containment of extremely hazardous materials. It also operates well in a completely evacuated vessel or containment system at pressure as low as 10^{-7} torr. A

sealed manipulator is shown in figure 3. It can be completely separated into three sections. All motions are converted into pure rotations which are transmitted through double rotary mechanical seals between the master and slave mechanisms. The interspace between the two seals may be pressurized with any suitable gas to serve as a lock permitting continuous monitoring of seal integrity. In the event of seal failure any resulting leak will only allow the compatible pressurizing gas to escape to either the master or slave compartment. The slave ends of these sealed manipulators are remotely removable, and replaced units couple up to the seal tube assembly re-establishing all motions initiated at the master end.

A third item I would like to tell you about is a small micromanipulator. This device can be used under a low-power, binocular-type microscope and it provides motion reductions of approximately 20 to 1. In the configuration shown in figure 4 a small tweezer or gripping tool is operated in opposition to a probe. The motion heads are capable of exerting fairly high forces under complete control with no backlash or lost motion. The operation is learned easily and quickly as the operator discovers that the microtools move like extensions of his fingers in the field of magnification. It is not difficult with the hands supported to achieve finger positioning to about a sixteenth of an inch. With a reduction of 20 to 1 it is no problem to position the tweezers or other tools to three thousandths of an inch. This provides complete control and enables retrieval of, or crude operations on, small particles.

In the nuclear field an example is the requirement to section some fuel which is approximately three-eighths of an inch in diameter. A thin cutting wheel makes a waffle-like grid on the circular cross section of the fuel sample. The micromanipulator makes it possible to select little samples from known positions on the sectioned fuel. Other applications come to mind in the biological and medical fields. The micromanipulator might also be operated by master-slaves and periscope optics to provide viewing in high radiation fields.

CHAIRMAN JOHNSEN: Questions, please. Mr. Allen?

MR. ALLEN: What is the cost of the micromanipulator?

MR. CHESLEY: It can probably be supplied for less than one thousand dollars and we are examining the costs for an initial production run.

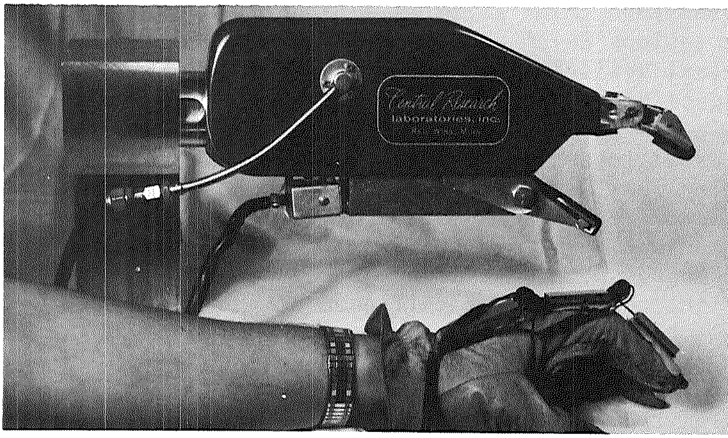


FIGURE 2.

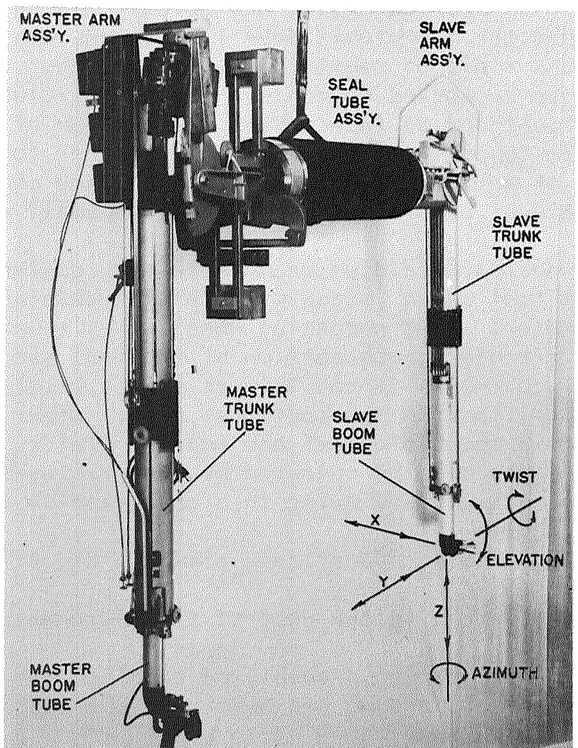


FIGURE 3.

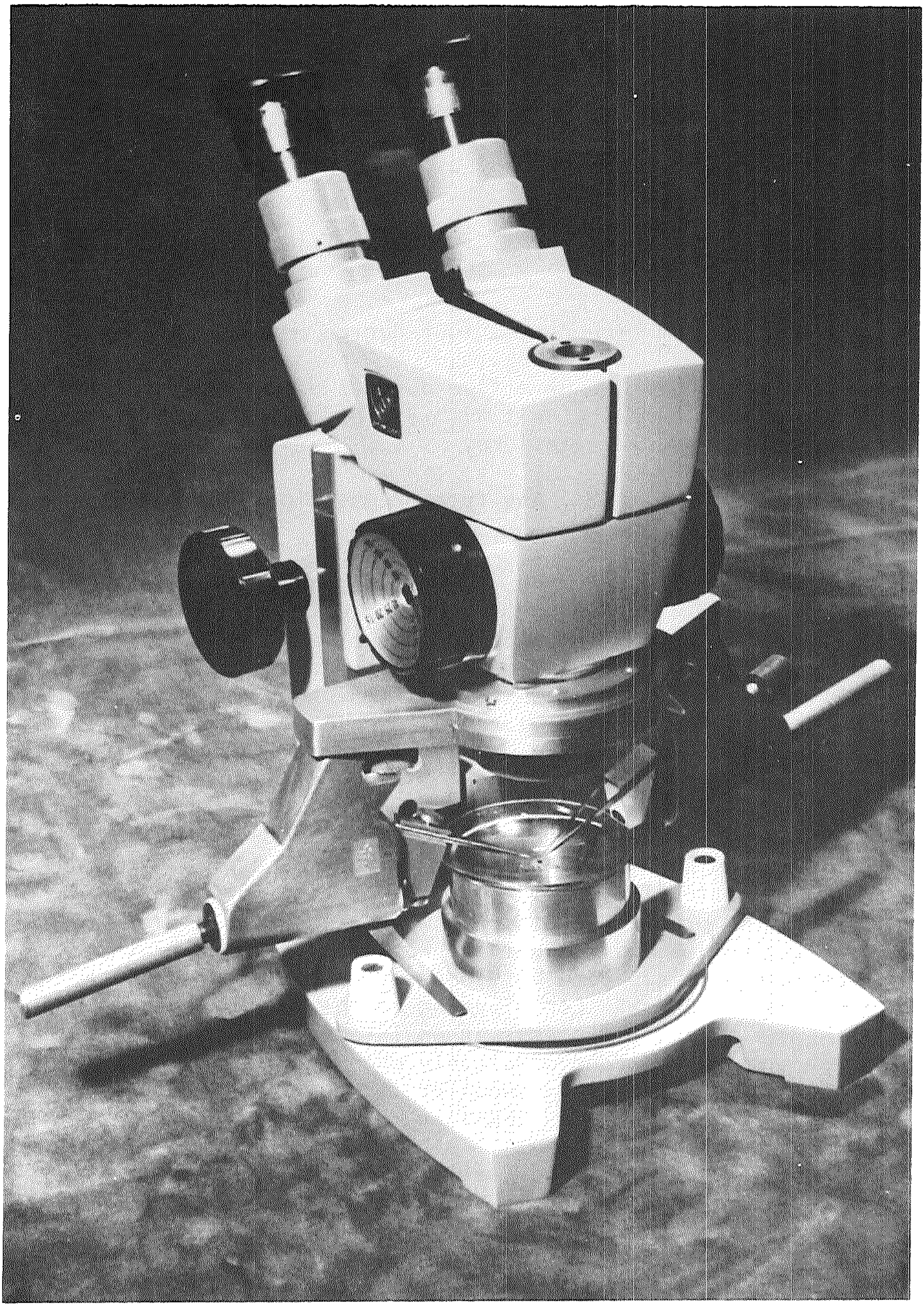


FIGURE 4.

MR. ALLEN: Is it available now?

MR. CHESLEY: No, but we are preparing descriptive information and hope to be able to distribute it soon.

MR. FLATAU: Do you have any kind of force reflection on the micromanipulator?

MR. CHESLEY: No. There is no useful force reflection involved.

MR. FLATAU: You have a four-degree movement?

MR. CHESLEY: We have five degrees of movement and a pinching action on the unit with a tweezer. The motions are X, Y, and Z and two rotations.

CHAIRMAN JOHNSEN: Any further questions? Thank you very much.

MR. MELVIN J. FELDMAN, Argonne National Laboratory: I would like to describe a research and development project that was carried through to practical operations. In 1958 Argonne conceived a project for remote processing of reactor fuel. This differed from what we normally think of as fuel processing in that it was a complete cycle which included manufacture. In 1960 the design was completed, and in 1963 the concrete was placed. By 1964 the process began its operation.

The basic process was a trial for remote operations. Superimposed on normal remote operation was a higher-than-usual radiation field (105 to 106 R-hr) and for a major portion of the process, an inert atmosphere (argon at 20 to 100 ppm) of water and oxygen. There was also a requirement to integrate nine separate but consecutive operations into a continuous process. Contributing to the complexity of operations was that the process was an integral part of a reactor complex which depended completely upon this facility for its fuel. So we were a sole supplier for fuel and were tied directly to the reactor (EBR-11).

In the layout of the facilities (fig. 5), there are two cells. The circular one is the more unique; it contains an argon gas atmosphere. The second is a fairly standard hot cell — air atmosphere, two-sided operation, normal rectangular configuration. Here the figure shows again the basic steps of the process as were shown on the earlier figure.

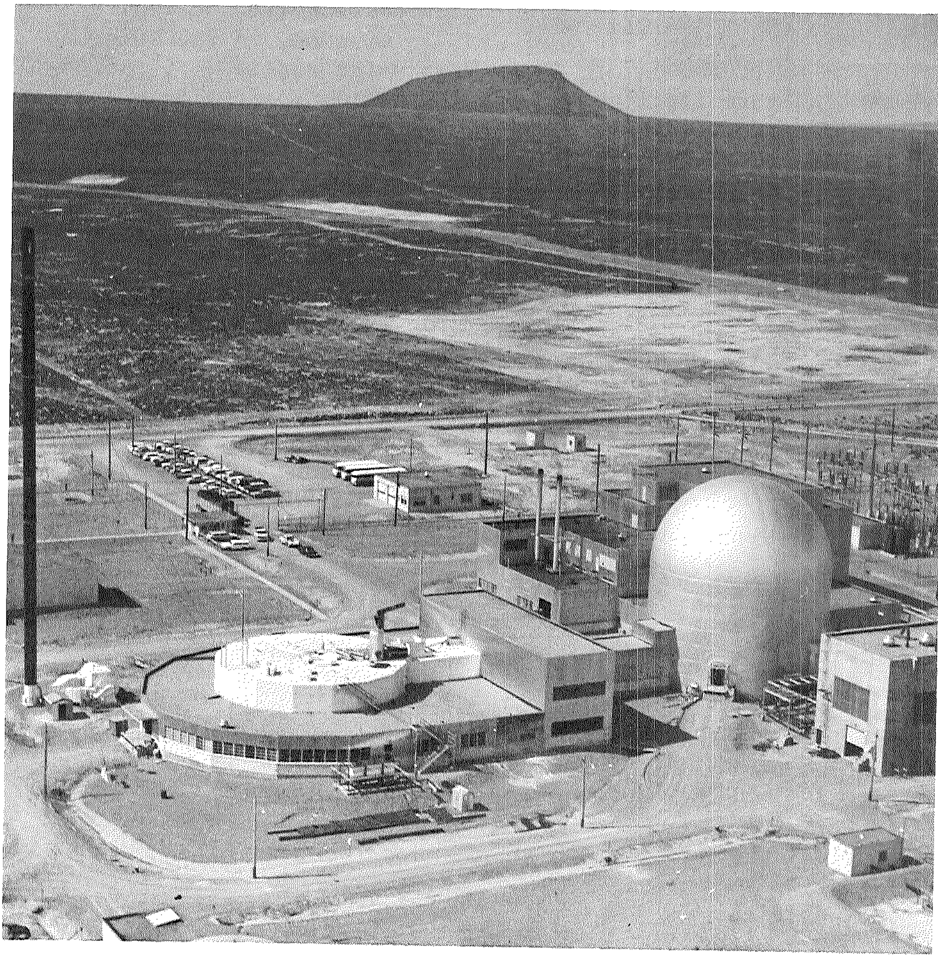


FIGURE 5.

Figure 6 is a schematic of the process. We received subassemblies from the reactor. This was our spent fuel. We dismantled the subassembly, moved the fuel cladding, and placed the fuel into a refining process. Following the refining step, the metallic fuel was, in essence, in the same condition as it was before it went into the reactor. Since it was highly radioactive, we then proceeded to fabricate the complete fuel element over again from the raw fuel to the inspected element. The finished elements are fabricated into a subassembly and shipped back to the reactor, in a continuous stream. Figure 7 is a cut-away of the building and the remote facilities. It shows the circular cell, the rectangular cell, and the passageway that leads towards the reactor. It also shows the peripheral laboratories. Figure 8 is an elevation of the circular cell. We have the ability to operate from the inside of the doughnut configuration or from the outside. As it turned out, the inside was used as an auxiliary viewing and control position. Standard rectilinear manipulators operating in polar coordinates had their cabling fed at the center of the cell. Figure 9 shows the fuel cycle facility and the EBT-II reactor. Figure 10 is a view of that manipulator from its center support column, showing the bridge and carriage. The bridge is a permanent installation; the carriages are removable for repair. There are eight of these bridges. The manipulator used in this facility was a stiff-arm crane with fingers at the end. It has a 750-pound capacity. Figure 11 is an end view of the air cell showing the equipment and master-slave type of manipulators. In this cell, we use the standard Model-8 master-slave; in the argon cell, we use the sealed master-slave manipulators. Also shown is the overhead system with the telescoping tubes extended. The carriage is interchangeable with those in the argon cell. We have continuously transferred carriages between the two cells. Figure 12 is a representation of the process: refining the metal, casting, molding, and shearing — a large number of steps. This is, in essence, a standard manufacturing process remotely operated.

Since start-up we have handled 2300 kilograms of exposed fuel and have manufactured over 35,000 fuel elements. This is a little better than five core-loadings for the reactor. I think one of the most important contributions of the operation is the fact that from March 1964 until the present time (five years), there has been no manned entry to the facility. All the operations have been done remotely. The design philosophy of the facility was that manned entry would not normally be required. We accumulated reams of statistics. I would like to touch on a couple of high points. We have 11 electric manipulators, 3 cranes, 21 Model-8 master-slaves, and 8 Model-A sealed master-slaves. We also established repair frequen-

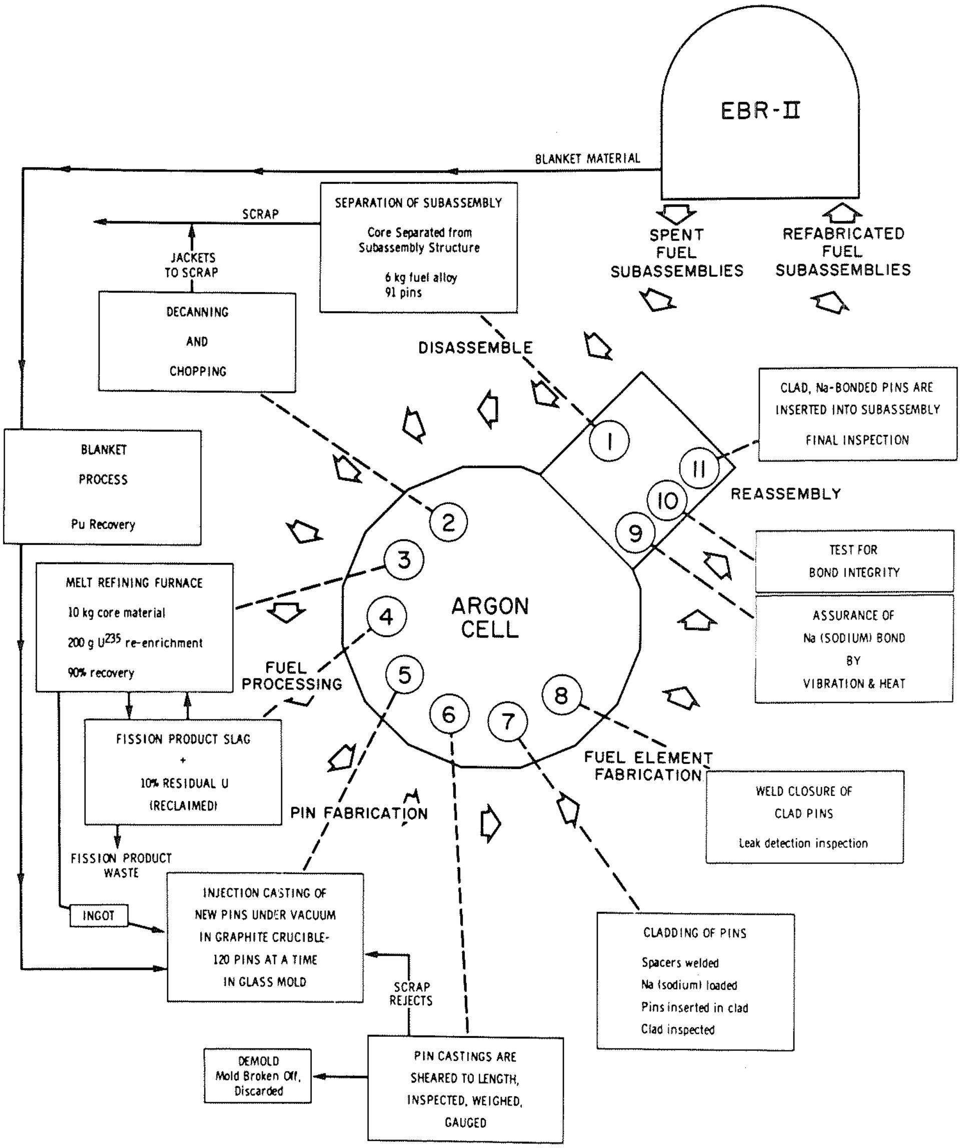

EBR-II
BLANKET MATERIAL
SEPARATION OF SUBASSEMBLY
Core Separated from Subassembly Structure
6 kg fuel alloy
91 pins
SCRAP
JACKETS TO SCRAP
DECANNING AND CHOPPING
SPENT FUEL SUBASSEMBLIES
REFABRICATED FUEL SUBASSEMBLIES
DISASSEMBLE
CLAD, Na-BONDED PINS ARE INSERTED INTO SUBASSEMBLY
FINAL INSPECTION
REASSEMBLY
BLANKET PROCESS
Pu Recovery
ARGON CELL
1
2
3
4
5
6
7
8
9
10
11
TEST FOR BOND INTEGRITY
ASSURANCE OF Na (SODIUM) BOND BY VIBRATION & HEAT
MELT REFINING FURNACE
10 kg core material
200 g U^{235} re-enrichment
90% recovery
FUEL PROCESSING
FISSION PRODUCT SLAG + 10% RESIDUAL U (RECLAIMED)
FUEL ELEMENT FABRICATION
WELD CLOSURE OF CLAD PINS
Leak detection inspection
PIN FABRICATION
FISSION PRODUCT WASTE
INGOT
INJECTION CASTING OF NEW PINS UNDER VACUUM IN GRAPHITE CRUCIBLE-120 PINS AT A TIME IN GLASS MOLD
SCRAP REJECTS
CLADDING OF PINS
Spacers welded
Na (sodium) loaded
Pins inserted in clad
Clad inspected
DEMOLD
Mold Broken Off, Discarded
PIN CASTINGS ARE SHEARED TO LENGTH, INSPECTED, WEIGHED, GAUGED

FIGURE 6.

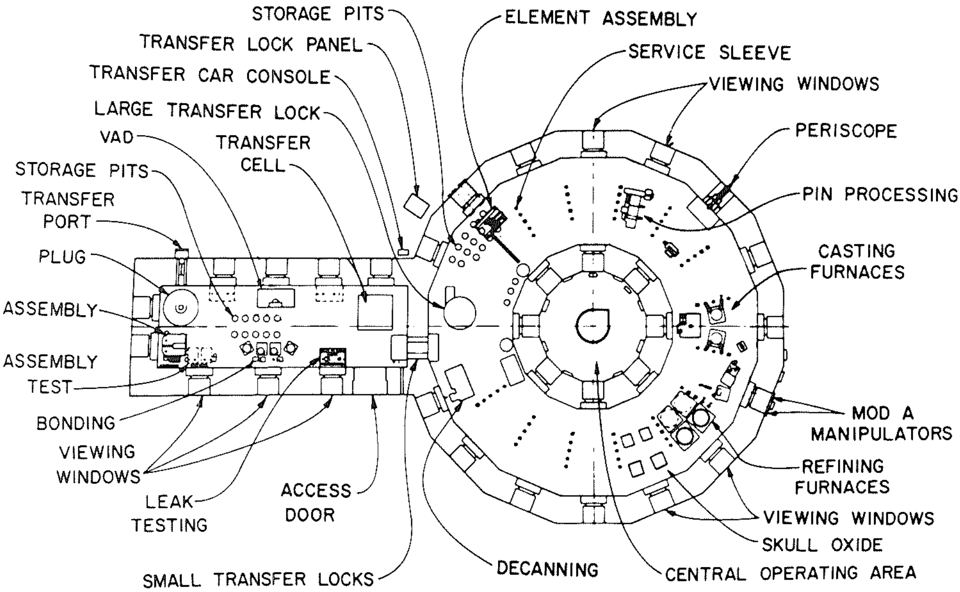


FIGURE 7.

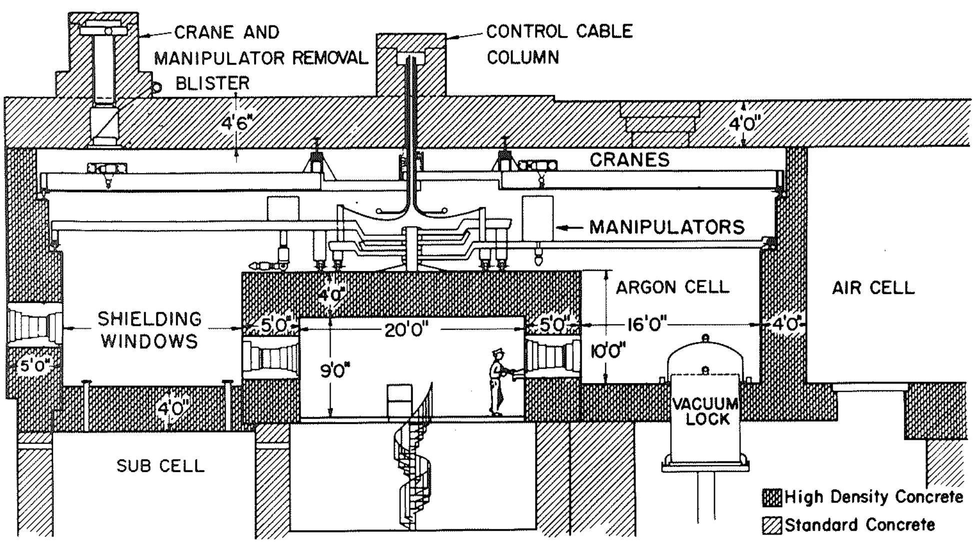


FIGURE 8.

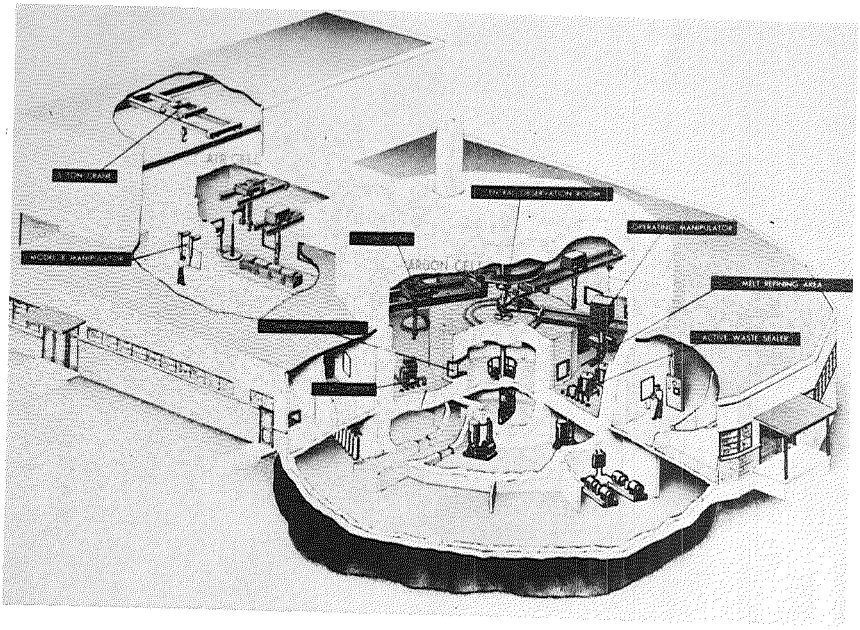


FIGURE 9.

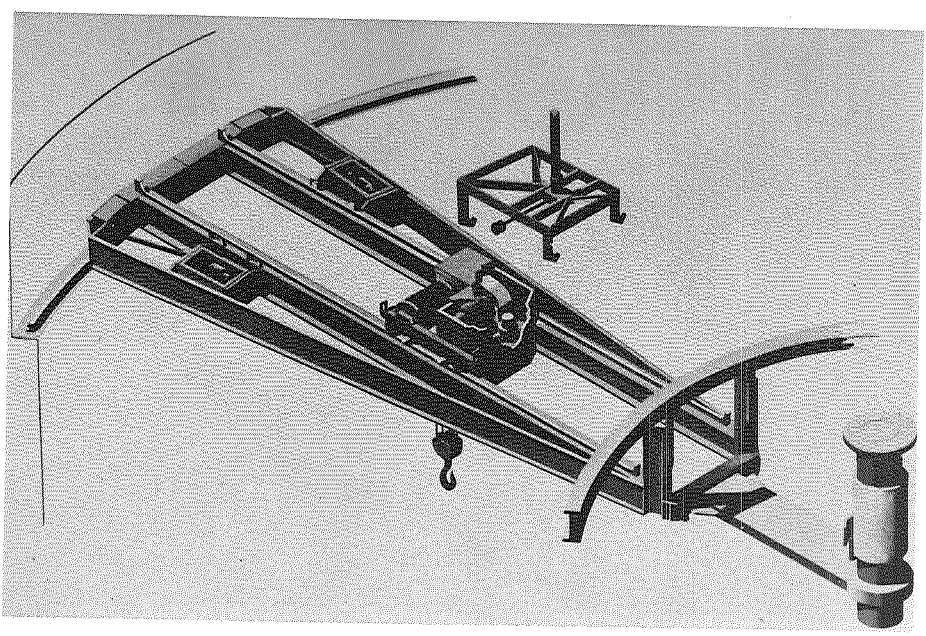


FIGURE 10.

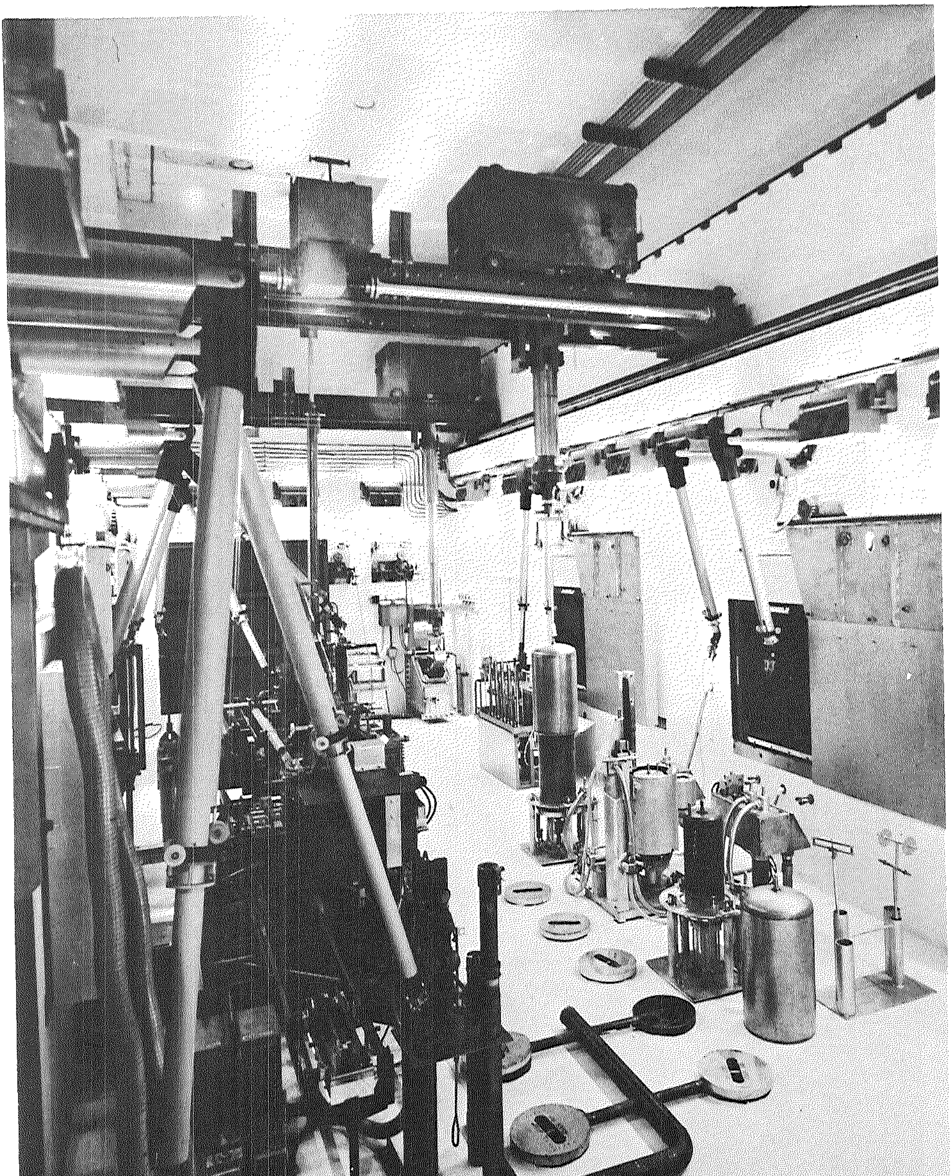


FIGURE 11.

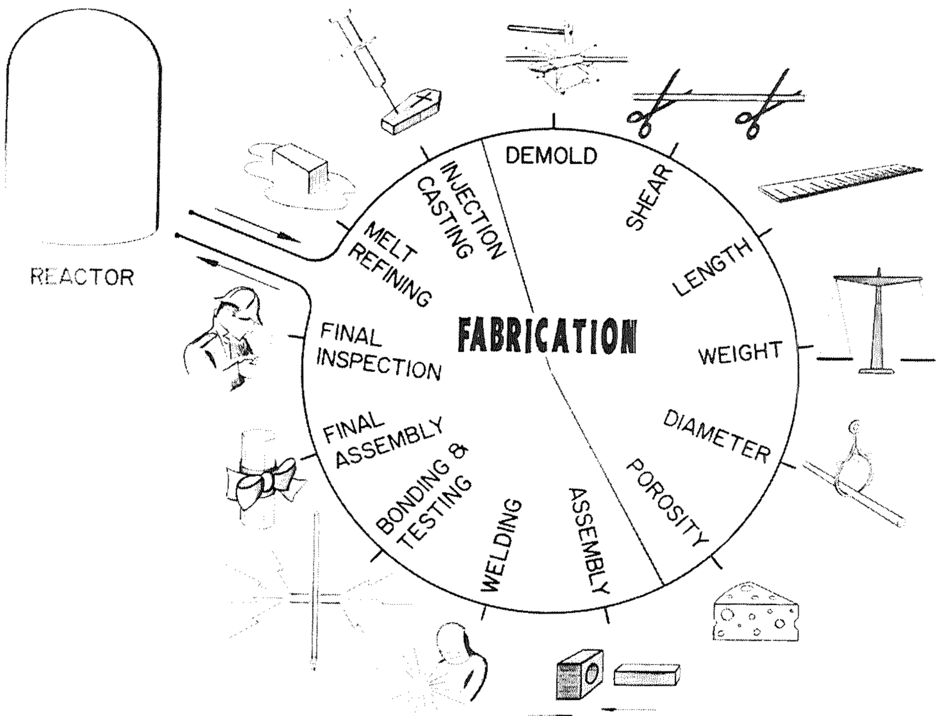

REACTOR
FABRICATION
DEMOLD
SHEAR
LENGTH
WEIGHT
DIAMETER
POROSITY
ASSEMBLY
WELDING
BONDING & TESTING
FINAL ASSEMBLY
FINAL INSPECTION
MELT REFINING
INJECTION CASTING

FIGURE 12.

cies for our equipment. On the Model A, a sealed manipulator is made up of three components: the outside master, the through tube, and the inside slave. These were treated separately. The repair frequency on a master was once every two months; on a slave, once every three months; and for the sealed tube, about once every two years.

On the electric manipulators, and there were eight of them operating almost continuously, we kept track of their ability to operate. We called the manipulator efficient if it was operable or operating. Most of the time we were processing fuel, so it would be in an operational mode, but there are times when you are not operating although the manipulator itself is available. Our electric manipulators ran between 61 and 96 percent availability. The average (for the eight) was 89 percent over a three-year period. These statistics were derived during the three-year span, our heaviest operations period. On the specific equipment that made up the process equipment the efficiency was between 80 and 99 percent. The average here was about 92 percent equipment availability.

In operating this remote foundry, we just proved that a complex sequential remote operation can successfully be undertaken. Second, where repetitive operations are planned, the equipment can assume some of the manipulations. Third, a force reflecting electric manipulator would have provided additional flexibility and efficiency in the operations. In addition we needed good resolution television to utilize the space in the facility. This was designed around the window concept, which leaves you with a band of operating area within the sight line of your window. There was additional space that we could have used had we had good-resolution television. We made some progress in convincing people that remote operating and remote maintenance and repair for processing plant and reactor operation are a potential avenue of pursuit.

CHAIRMAN JOHNSEN: That is a lot of experience. Questions?

QUESTION: If you plan to have a complete remote operation, how are you going to repair the manipulators?

MR. FELDMAN: One of the things that you look at when you analyze remotely operated fast reactor systems is that there is a requirement for remote service facilities built right within the same containment shell.

QUESTION: Will a man actually have to be in contact with these manipulators to accomplish repairs?

MR. FELDMAN: There are many repairs on the electric master-slave that another slave can make. There are some repairs in which you have to have an avenue where you get manned approach, either a glove wall or a tunnel suit. You can always take the approach that when something malfunctions, you replace it. We did not find this a feasible approach and that may just be a comment on the state of the art.

QUESTION: You illustrated the large overhead manipulators and mentioned these could also be repaired. What reaches them?

MR. FELDMAN: The illustration showed a fixed overhead crane. These are two-tiered systems so that a crane can remove a manipulator. About that is a fixed crane, and the bridges are free wheeling, and so with another bridge you can always push a bridge over to the correct position and retrieve the carriage. We have had to use this mode of operation twice in five years.

QUESTION: I presume, since there was no manned entry, that replacement parts were transferred into the working area.

MR. FELDMAN: Yes, in a continuous stream. One of the major problems of this operation was the extremely high levels of contamination that were generated. Repairing the modules we removed became a serious contamination problem. The original concept of the facility was to throw away malfunctioning equipment and replace it. As the reactor became more reliant on our fuel production, we lost the freedom of shutting down. Under those circumstances, we learned the art of decontamination and repair.

DR. MURPHY: Is there enough buffer storage of fuel elements in the system so you can stop a given operation for a short period?

MR. FELDMAN: Yes. We ran a three- or four-day material inventory at each step in the system.

CHAIRMAN JOHNSEN: If you had to do it over again, what would you change in order to make it an even more efficient system? You would use television for one, I gather. What else would you do?

MR. FELDMAN: I think if you couple our experience with the availability of mobile television and freely moving force-reflecting manipulation, we would build a large, windowless,

shielded area. Signals from both the manipulators and from the operating equipment would be fed to data systems. The computer would be programmed for all normal operational control. Man would be required only to initiate special programs.

MR. FLATAU: If you had to do it over again, would you find an electrical master-slave that would work above the shoulder useful in servicing such a facility?

MR. FELDMAN: Yes, we had to have a heavy overhead system to handle some of the pieces of equipment. With such a system, we could have used electrical master-slaves many times overhead to repair that system. The present removal system provided a very tortuous repair path.

CHAIRMAN JOHNSEN: Any more questions? Thank you very much, Mr. Feldman.

We are going to change the agenda a little bit now because of the visual requirements. Our next speaker will be Dr. Kleinwachter from Germany.

DR. HANS KLEINWÄCHTER: Ladies and gentlemen, I want to show you a 12-minute movie about my activities during the last 12-months in the field of master-slave-system development. On a visit four months ago here in the States, a short film presented by me was so well received that I have been encouraged to proceed with the development and in the meantime I have made a longer film. Yesterday and today a lot of devices similar to the one I will show you were demonstrated; but I believe that is no reason to stop the work. I think there are some gaps in the master-slave development which give reason to cooperate in this technology. I hope the synchronization of my film will be adequate, as I have movie and tape separate. This film will show you the state of work development for realization of an anthropomorphous machine, carried out in my research laboratory, in Lörach, Germany, during the past 1-1/2 years by order of the German Ministry of Scientific Research.

This machine is designed to enter radiation-intensive rooms in the place of human beings in case of nuclear accidents. It can also carry out complicated missions of diagnosis and operation. For easy handling and versatility we have decided on a master-slave system with an exoskeleton as master commanding device and a biped, walking-slave machine. Before my visit to Idaho Falls, at the Argonne Institute, the Marshall

Space Center, and General Electric four months ago, I did not know about the high state of development of remotely operated devices in the U.S.A. By then, we had already named our master-slave system "Syntelman," as an abbreviation of Synchron-Tele-Manipulator. Here you can see the result of an experimental feasibility study. We fixed this up within a few weeks by using marketable toy gear motors, trimmer potentiometers, and power transistors to a master-slave system of five position-controlled degrees of freedom (fig. 13).

Because of the restrictions of the master's exoskeleton to five degrees of freedom, the strong torsion-muscle of the upper arm had to be blocked, and this led to a heavy constriction. Nevertheless, with this simple slave system, using a portable master exoskeleton, we could carry out the complicated manipulation of taking a container and decanting its content. By the aid of the means made available for us after the feasibility study and as a result of experience, the model (fig. 14) shown here of a stereo television-operated master-slave arm system was evolved. This features seven controlled-angle and two not-transmitted lateral degrees of freedom. The seven electrical drive-motors of the slave arm are attached directly to the joints with their reduction gears and positioning potentiometers. The exoskeleton of the master is made very light and can easily be fixed to the master. To obtain a low total weight all motors are dc collector types and disk rotor. The angle coordinates of the slave do not follow the angle of the master. This is because silicon-controlled rectifier amplifiers presently drive the motors far below their thermic power limit. Little transmission mistakes to the slave arm hardly cause trouble, as they are compensated by the master of the optic feedback of the used stereo television system. The six transmitted degrees of freedom of the slave's hand seem to be sufficient for its manipulation. However, the additional degrees of freedom of the thumb-forefinger tongs are definitely insufficient for delicate manipulations. In cooperation with German experts of hand prosthesis, a versatile hand of more than one degree of freedom will be developed in the future.

The following film sequences provide detailed information about the usefulness of the chosen stereo television system (fig. 15). The master sees the chessboard that is placed behind him only on the stereo television receiver. For this we have provided a pair of television eyes in anthropomorphous position to the slave arm. By using both the differently polarized pictures of the left and right television eye and suitable analyzer glasses, the master obtains the tridimension-

al picture of the room of operation. This enables him to take and move chessmen without touching the neighboring one with his slave finger. The insertion of a screwdriver into a borehole of only eight mm indicates the accuracy obtained at present. This mainly depends on the mechanical gearboxes and in the future will become considerably reduced. The correct handling and use of a tool will be facilitated by a second hand, and a slave hand of several degrees of freedom, and fingers. For this the rotation axis of the screwdriver does not have to be that of the forearm. For a Syntelman operating in the reactor it might be important to be able to manipulate a power supply plug (fig. 16).

The turning of a screw with a wrench, using one hand with the primitive one-limb tongs, is complicated too, but still feasible — that is, providing the tridimensional stereo system supplies sufficient information. For routine work with screwdriver and wrench, hammer, chisel, etc., slave-motor-driven special tools are needed which can be attached to sockets on the right working hand.

The following slides show some construction details of the slave arm and the master-exoskeleton arm belonging to it (fig. 17). The thumb-hand tongs have in this simple form the usual parallel lead. The motor power of each of the joints is adapted to the proportions of the power of the human arm muscles. The thumb-hand tongs, the hand nick joint, and the forearm rotation joint as well as the elbow joint are driven by small iron rotor motors, and the three shoulder joints by high-power disk rotor motors. The master's arm moves the attached light exoskeleton. This has seven degrees of angle freedom, which are combined with minipotentiometers and control the position of the slave arm. Besides, the exoskeleton has two lateral degrees of freedom, which allow minor changes in length of the upper arm and forearm of the exoskeleton. Both of these additional degrees of freedom are not transmitted to the slave arm and avoid undesirable forces when moving the exoskeleton. The television receiver consists of two normal small-picture receivers, which show the separate images of the left and right television eyes at different polarization. The master observes both pictures over a semitransparent mirror through special polarized glasses. This gives him tridimensional information of the operation room. This picture shows the control specialty developed for Syntelman. Owing to the low-power dissipation, all of the seven 200-watt amplifiers could be mounted closely together. The stability of the seven

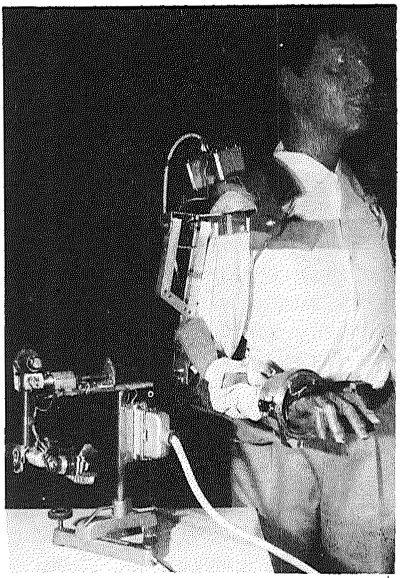


FIGURE 13.

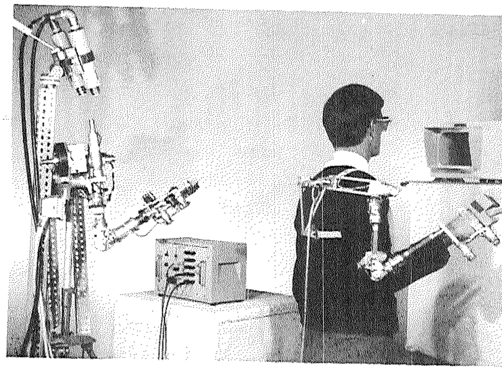


FIGURE 15.

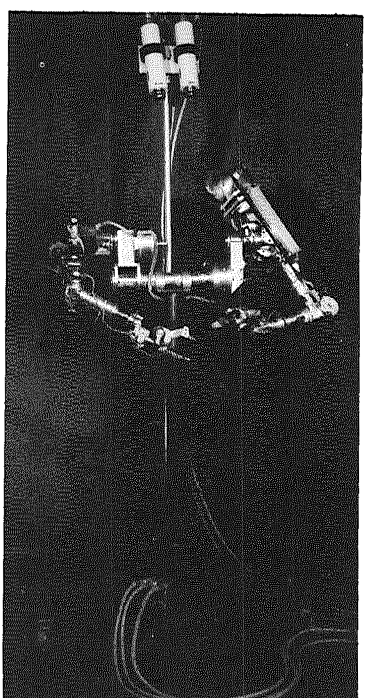


FIGURE 14.

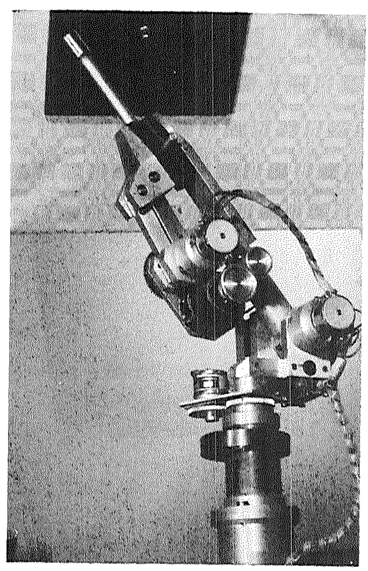


FIGURE 16.

control loops was obtained by phase control and angular speed addition. The motors are prevented from overloading by temperature sensors and thus can produce much over power in cold condition. We regard as provisional the use of quick-running electric-drive motors with their power-losing reduction gears. These must be replaced by gearless fluidic motors as soon as possible.

This slide (fig. 18) shows an early laboratory model of a fluidic muscle, which converts the pressure energy of the fluid into torsion work. This occurs by means of a membrane, the elasticity of which becomes anisotropic through a tight arrangement of steel wire. Except for drive rails and long plain gangways, all installations such as stairs, ladders, door entrances, hatches, etc., are adapted to the biped motion of man. We therefore intend not only to put the slave-arm system on wheeled and tracklaying vehicles, but also on anthropomorphous biped walking machines.

For the quasi-static biped walking, the center of gravity of the slave must constantly be situated over the contour of support. Consequently the projection of the center of gravity for standing on one leg must be within the contour of the standing leg, and for quasi-stationary walking, must follow the zigzag path, visible in the film as a shadow (fig. 19). While the angles of the slave's legs are commanded by the master, this motion of the slave's center of gravity must automatically be controlled by power sensors of the slave's ankle joints.

The last sequence of the film shows the dynamic, quasi-biped walking of Hong Kong-made toy dogs periodically shifting the center of gravity dynamically by a resonance vibration. We hope to outstrip the lead of the Chinese in this field of walking machines shortly.

At times yesterday and today it was mentioned that the hand still is the weakest point of the master-slave system, because we used six degrees of freedom, three Cartesian and three angular coordinates for placing the hand plates, and we left only one additional degree of freedom for the finger-hand tongs. Increasing the number of degrees of freedom for the hand by one, two, or three would increase the versatility of the hand considerably. For this I cooperated with a German expert for prosthesis, who started his work back in 1945, a rather hostile time for starting a company. After one year he had realized an artificial hand. Now I hope that gentleman

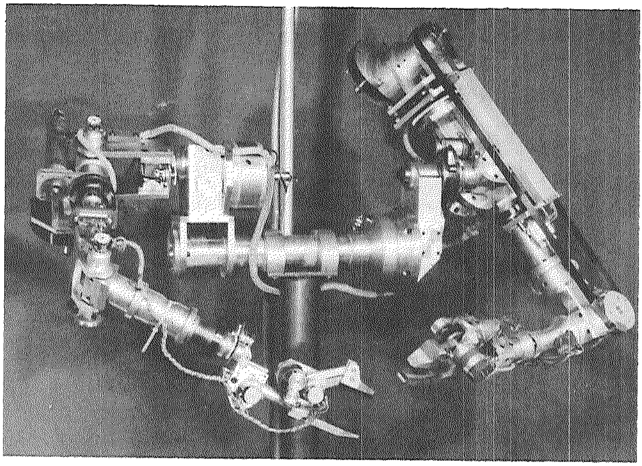


FIGURE 17.

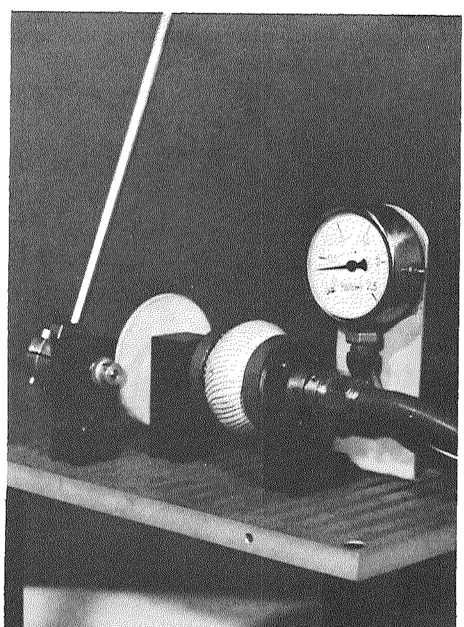


FIGURE 18.

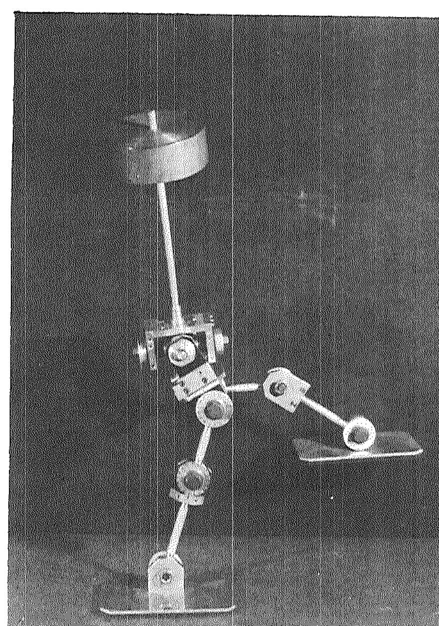


FIGURE 19.

will help me to improve the hand mechanism. In closing I want to thank you for your kind invitation and for your patience in hearing my self-taught English. If you come to old Europe, spend some time in the nice Lörrach, my home. Many thanks.

CHAIRMAN JOHNSEN: Any questions?

MR. FLATAU: I have two questions; a remark first, on terminology. I think when the term master-slave was coined — and I believe Ray Goertz can bear me out on this — it was intended to mean bilateral master-slave. This means one can have both the master by the slave and the slave over the master and thereby also achieve force reflection. I don't want to say this is not a master-slave, but we ought to try to keep our terminology straight so we know what we are talking about. As to the two questions. First, on the biped model with the center of gravity control, it seemed to me this was an animated thing and not powered, is that correct?

DR. KLEINWÄCHTER: This was a simulation of the static mechanism. I learned of this problem from Mr. Mosher four months ago, and we then reflected how to walk statically, not dynamically. That means, as long as the walking machine stands on one leg, the center of gravity must be inside the contour of the leg; and now before we lift one leg we must displace the center of gravity to the other leg. The master controls the angle of the limbs of the slave, but the control of the center of gravity has to be made by the slave's own intelligence. This can be done by measuring the forces and the torques in the ankles of the legs in cooperation with a computer.

MR. FLATAU: May I ask my next question? You talked about planning more than one degree of freedom in a terminal device, let's call it. Could you say a few words about what your next approach will be?

DR. KLEINWÄCHTER: The next step will be to realize a mechanical hand similar to that Dr. Koennecke developed in 1945 and adapt it to our slave arm.

CHAIRMAN JOHNSEN: I am going to have to cut off further questions. We have got to compress things now.

Thank you very much, Dr. Kleinwächter.

Mr. Schlissler.

MR. EARL R. SCHLISSLER, Westinghouse Electric Corporation: It looks like most of the manipulators that have been discussed so far are those which are used in hot-cell work, programmed within industry, and some which are master-slave types, but I want to talk to you about an underseas manipulator. Our Ocean Research and Engineering Center at Annapolis, Maryland, is currently building a manipulator for use on the deep-submergence rescue vehicle. The primary mission of this vehicle will of course be that of rescuing personnel from a distressed submarine. The role of the manipulator in this case is to clean debris from the distressed area, cut a messenger buoy cable, and grasp and pull down a haul-down cable to which a grapple is connected, and attach it to the bail of the escape hatch. So in this case we have predetermined tasks for the manipulator to follow. I regret that I don't have any slides for my talk this morning, but the hardware is not yet complete. So I will have to give you a word description of it.

In general, the manipulator system consists of an electrically operated, hydraulically powered, mechanical arm, which uses the vehicle hydraulic-system power. Its control unit consists of two parts. One is a rack-mounted electronics box and the other a control-input device to which is mounted a joy stick. The joy stick has three axes of rotation, can be displaced fore and aft, operated from port to starboard, and can also be rotated. These motions will result in various manipulator actions, depending on the position of a thumb-operated five-position toggle switch located near the top of the stick. There is also a small push button operated by the thumb which can be depressed to cut the cable when necessary. In addition, there is a trigger switch mounted on the far side from the operator, which is used to operate the jaw bar.

The arm is ten feet long; it is capable of exerting 50 pounds of force in any direction and in any position. Further, it has a requirement that it be capable of resisting a 600-pound force in certain arm configurations, when being pushed or pulled by the vehicle to move debris from the general area of operations. The arm has a shoulder rotate, shoulder pivot, and elbow pivot joint as well as three wrist movements — vertical, horizontal, and roll. Additionally, it has a multipurpose terminal device, mounted at the arm extremity, combining the functions of a cable cutter which cuts a five-eighths-inch diameter wire rope; a jaw bar which can be adjusted for grip force from the operator's control (zero to 2000 pounds); and a high-speed brush/pump assembly used in cleaning the escape hatch of the submarine.

Because the manipulator could become inalterably entangled in the work function, a jettison system is necessary. In this case we have a capability of jettisoning the entire arm from a point just above the shoulder-rotate joint with two completely redundant systems for doing this. One mode is actuated by the hydraulic power supply, and the second system is gas-operated from a high-pressure bottle, which is initiated by a squib. In addition, the terminal device itself can be forcibly ejected, hydraulically and remotely, or it can be removed manually. This function is not necessary to the mission, but is required for future work where an interchange of tools would be useful. Probably the most significant feature of this manipulator is its control system which employs both rate and position feedback and has an analog computer to provide three basic modes of operation. There is an automatic stow and unstow mode, a so-called true-arm extend and retract mode, and then there is a manual mode.

Let me talk about these individually. To improve the vehicle's hydrodynamic characteristics while underway, it is necessary that the manipulator be brought up inside the ship's fairing, which is an extremely small opening. So the arm must be folded through seven discreet steps to get it into place. The reverse procedure is also true. There is a single command given by the operator and the arm then goes through the sequence of motions until it is completely unstowed or stowed, as the case may be. A mode selector switch is situated on the control—input device that the operator must position when he wants to go from one mode to another. Then there is an additional control knob which enables him to execute the function.

In the automatic mode, during each step one joint is commanded at a constant augular rate, and one or more other joints are slaved to the output of the commanded joint rate. To get it into the stow mode, the arm has to be brought into a prestow position. This is accomplished by getting it to a position which essentially is where the upper arm, the forearm, and the terminal device are more or less horizontal and out to starboard. The operator knows when it is in this position because he has a series of lights situated on his control-input device which will light and let him know when he has every joint in its exact position. When he does have everything ready, he can then execute the command to stow, and it will do so.

The true arm-extend-retract mode is required to eliminate time in cleaning the hatch. On this vessel a transfer skirt is attached to the underside of the midsphere. This skirt is made to mate with a similar kind of hatch surface on the distressed submarine, and in order to get a good seal, any dirt or other debris that may be on that surface must be cleaned off. To do this most efficiently you should have some sort of translatory motion, and that's precisely what this mode can achieve. A coordinated motion of the shoulder, the elbow, and the wrist pivot joints causes the terminal device to move in translation along the center line of its longitudinal axis. Depression of a thumb switch on the joy stick automatically puts the arm into that mode of operation.

The manual mode is simply the normal mode of operation when we are not using the computer. Operation of the joy stick gives a rate signal which is proportional to the displacement of the joy stick.

In hydraulic devices such as this, leakage through check valves is undesirable since the manipulator must hold position when the command is removed. Hydraulic leakage sometimes allows the arm to drive to an undesirable position. We solved that problem by use of an electric equivalent. As the thumb switch is depressed, the position loop is opened and a "track" command is entered into the track-store circuitry which tracks the slewing-position transducers. When you release the switch, a store command is entered into the track-store circuitry and compared to the position transducer which is situated on the joint of the arm. This prevents drift. I think that about covers the mechanical and electrical characteristics of the device. I do have a set of write-ups over here which go into much greater detail for those of you who are interested.

CHAIRMAN JOHNSEN: Thank you. Any questions?

QUESTION: How does the operator view the manipulator in the manual mode? Is he looking through a porthole or external camera?

MR. SCHLISSLER: A couple of portholes are provided. This vessel has three pressure spheres which are interconnected—a forward, a midsphere, and an aft sphere. The manipulator is situated in between the forward and the midsphere and there are a couple of portholes provided in the vehicle through which the manipulator can be seen.

QUESTION: The fact that there is an air-water interface which distorts the field of view — does that give you any trouble?

MR. SCHLISSLER: I am told that it does. That is not quite in the field we are involved in here, but occasionally it does. What kind of study has gone into that or what kind of window specifically they have, I don't know.

CHAIRMAN JOHNSEN: Thank you very much, Mr. Schlissler.

Mr. Jones.

MR. JAMES JONES, NASA: This is my first appearance with you people and I would like to begin by introducing myself. I am in the Ames Research Center and our organization runs: Man-Machine Integration Branch, Biotechnology Division, Life Sciences Directorate. My particular group is Man-Machine Integration. We are developing from a piloted-airplane-interface interest into a broader spectrum. As a result of conversations with Mr. Johnsen, we have undertaken to get into the space aspects of remote manipulators. Historically, we have funded a variety of studies in the remote control of vehicles, a variety of sensors, and sensing methods. At present we are attempting to obtain a surplus pair of 500-manipulator arms — not the bridge crane but the arms. Am I correct on that?

CHAIRMAN JOHNSEN: No, these are the bridge cranes.

MR. JONES: It is less than the crane, though?

CHAIRMAN JOHNSEN: That's right.

MR. JONES: We will be doing some computer-augmented work with at least one of these manipulators. I have become involved in the remote television-viewing system and am in the process of getting some hardware put together for the most simple system that I can imagine providing stereo television. I hope to avoid some of the problems that have plagued stereo systems in the past, in particular to consistently obtain a pair of compatible images. We are presently at the bread-board stage of developing an automatic focusing device for television. We have about four working configurations lying around on the work benches, but I am not far enough along to attempt to describe them yet. We haven't decided on what course to take with these things. I am working rather closely

with people who have optical training, and we feel optimistic about being able to put this stereo pair through the television system simultaneously and avoid the problems of dissimilar distortions. I think that essentially covers our endeavors.

CHAIRMAN JOHNSEN: Any questions?

QUESTION: Could you just say a word more about the nature of this computer augmentation you are planning?

MR. JONES: This is a co-worker's bailiwick. I can't say anything definitive about that.

QUESTION: Is there a report available on this?

MR. JONES: At present, no. It has just entered the realm of physical reality.

CHAIRMAN JOHNSEN: Thank you very much, Mr. Jones.

Mr. William Allen, also from Ames.

MR. WILLIAM ALLEN, NASA: To set the record straight, I am housed at Ames in a tenant organization called the Mission Analysis Division. I do paper work. Since we are short of time, I am going to put the most important information on the blackboard, then if I run over ten minutes, you tell me. The only thing we've got going is a contract with General Electric to study the use of remotely controlled manipulators for repair and refurbishment of satellites in orbit. General Electric's work on this study is reviewed by Interian and Kugath in "Astronautics and Aeronautics," May 1969. Essentially what we want to look at is: if we want to repair a satellite in orbit, what can we do with a manipulator? We want to keep things fairly crude, not do a soldering job or anything like that. We are looking at what we could do if we had a wrench and a screwdriver 20,000 miles long. You will see samples of the techniques considered in a film that Ralph Mosher will show.

During some of the conversations we had last night, I found that in several instances you were talking about much finer work with manipulators than I have in mind. I worked my way through high school and college as a rigger, working in cold weather with heavy gloves, hanging by one arm and one leg, and trying to break loose a rusted nut. So when people

talk about manipulating in a chem lab, I'm not with it. The Army took care of me for several years after I got out of college and always managed to put me in places like Greenland or the middle of the Amazon jungle, thus I have a feeling for severe environment.

One of the few things I had going for me during World War II was an arrangement with the Air Transport Command, when I was in Greenland, to bring me late magazines. We got some astounding science fiction in a story by Robert Heinlein about a guy who invented a thing called a Waldo. The Waldo was a master-slave glove arrangement. You worked with a glove and it went out to a slave, another glove, that multiplied force or diminished it — any number of wonderful things. Heinlein gave no details, just the concept. So when we sat up there in Greenland and had to go out in 40-mile wind, 30° below zero, to clean the snow out of a switchbox so we could push a button, we really hoped for a Waldo. That's what I have been hoping for in all this work up to now.

The General Electric study is basically a cost effectiveness study of a complete system. We are not contracting with this company to develop a manipulator, although they do have a design. We are seeing how cost effective this would be on a realistic task and we are biasing the study against the manipulator. Costs are included that really should not be put in, such as supporting technology. We are trying to make it look as bad as possible, but it still looks fairly good for some purposes. What is happening is that spacecraft, even unmanned, are getting more and more complicated. Those of you who have done any maintenance work know that as the design gets more complicated, you eventually reach a point where redundancy introduces unreliability. So you need some sort of a repair operation, and we feel that as the unmanned spacecrafts are designed to do everything that is wanted of them, we'll eventually get to this point. We have already proved the need for maintenance on manned spacecraft, where the man has to be there to do the repair even for things that are not necessary for his survival. We feel that maintainability is going to have to come or we will have a compromise. If we can't build in a cost-effective repair capability, then we are going to have to go to, say, satellites with single functions which can be replaced easily and for low cost, because the cost of sending up a large load is hard to visualize for those of us who aren't in the business.

To answer the question that came up last night, we consider our human factors data on man-machine interface with manipulators sufficient except in one very important area — time delay. We would like to see some more work on this, but we really feel that the operational systems or possible operational systems ought to be developed, the hardware made, and then we would like to see what the human factor problems are. We equate the manipulator system to a man in a space suit, or to get back to my own experience, to a man in heavy clothing and work gloves. This is essentially the type of repair we are talking about.

The other thing we are working on is, without any contract, the expendable astronaut; and again I am talking about a complete system study, not the hardware. The problems of using a human being in a space suit to do exploration or to, say, inspect a satellite, or find out what's wrong with the satellite are pretty rough. You introduce a whole new echelon of people involved in controlling the astronaut, looking over his shoulder, and monitoring him, and the support costs are unbelievable. However, if you lose a remotely controlled manipulator, you haven't killed a man, and you haven't lost a space program. We are taking a look at some of the tasks which were originally planned for manned operation and saying: "What could we do with what we can expect in the state of the art in manipulators, if we could get a manipulator in place of the man." Some of the plans that have been published assume that the required manipulator and associated equipment exists, but we just can't find it.

CHAIRMAN JOHNSEN: Yes.

MR. ALLEN: I hope to get more interest in this problem of the expendable astronaut from the people at NASA who control the money. I take every chance I can get to write memos when some authority makes a statement about what we are going to do in the far future, seven or eight years hence. I write him and say: "Look, it is going to take seven years to develop this thing and we haven't even given a contract for Phase A on it. When are we going to start?"

To break off here, in the work that General Electric is doing for us, we are talking about a known piece of equipment to do a very elementary type repair or replacement of black boxes, things like that. It is a preliminary system study in which we are looking at what a manipulator — a Waldo — with all the bugs out of it, could do if we had one.

CHAIRMAN JOHNSEN: Thank you.

Any questions?

MR. FLATAU: A remark on this charitable institution. I think it exists. We have a few very dedicated people, most of them in this room, who get ulcers and other things trying to carry these projects through without funding. There is also hardware close to what we need; it needs a lot more development but the ideas are there.

MR. ALLEN: Excuse me, when I was talking about unavailability, I had in mind space, and the space qualification of this hardware is a tremendously long process.

MR. FLATAU: I think I have some idea of what you are talking about. The idea is there for what needs to be done.

CHAIRMAN JOHNSEN: The engineering is the smallest problem.

MR. FLATAU: One more thing. I had a talk yesterday about a manipulator, and a few weeks ago I added up, very truthfully, what it cost the funding agency, including my salary, and so on. And once more the estimated cost is about to go up. It costs about ten times as much as the development of that manipulator. So you have an idea that the cost really, in NASA's budget terms, is enormous. I think you can find the space for that much money if you really want to.

MR. ALLEN: You could find it if it was in the proper pocket. Mr. Johnsen can explain it in detail.

CHAIRMAN JOHNSEN: What it boils down to is that there is a lot of convincing to be done yet. Many of us have been working on people, trying to convince them that they ought to put money into this thing. We haven't succeeded yet.

MR. JONES: That's about the size of it. I think we are making progress, but one of the things actually has been that human factor studies have always been labeled manipulator studies and people will say, "Oh, gee, we are studying manipulators," when actually they are studying just an interface problem.

CHAIRMAN JOHNSEN: Thank you very much.

DR. MURPHY: Don't you think one of the problems related to the point Mr. Jones made is the tendency of everybody to talk in the present tense, as if something in fact existed.

CHAIRMAN JOHNSEN: I think that is a part of the problem. The other part is a reluctance to admit that man maybe needs to be augmented. NASA is devoted to man in space and with all the capabilities of man, and perhaps they really don't like the idea of augmenting him, except the astronauts are beginning to get a good idea themselves. It is not so much a political as a psychological problem. I don't know when we'll luck out, if we ever will. We keep plugging.

Our next speaker is Mr. Mosher.

MR. RALPH MOSHER, General Electric: I could talk all day on manipulator technology. In the discussion period I want to bring out points of interest. I'll be here.

QUESTION: Can you show us about two or three minutes of your movie?

MR. MOSHER: Not yet. Here on the blackboard is progress twenty years ago. This meeting shows tremendous progress, and we are right there; if we can congratulate the University of Denver, I think this is a wonderful catalyst and I am impressed. There is only one dilemma; the frustrations are shown here in many cases. I notice some interesting developments, but as an engineer who loves his work, I am disappointed to see a duplication of efforts. As a businessman, I am glad. So I think that's the way to impress on you we should look at each other's work here and get this stuff going.

Nevins from MIT put a matrix of numbers down, didn't he?* I haven't seen anything like that around with regard to manipulators, and a couple of people challenged his numbers. Well, I again challenge the challengers to improve the numbers and publish them as Nevins did. That's one way of getting started. Now, of course, the dilemma is to try to duplicate the fine control of man. In order to match human performance you need to reflect his kind of efficiency in controls. The same curve applies to the acuity of tactile sensing of the fingers. That is when you see how efficient and fantastic

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*Mr. Nevins' talk is presented later in the proceedings.

man is. You want something in space that duplicates man's efforts in some ways. We have got to become very clever about it.

Again, in measurements, Mr. Flatau said something about the dexterity quotient. That's a step in the right direction. So far robots are spastic imbeciles in terms of potential and needs (fig. 20). I think we should measure servo performance or control capability. The resolution, the speed of response, the threshold of force, force bias, and viscous drag — these should all be measured. We are making attempts at that. We have started a matrix in our own plant, and this is something we need and it will help. Now we can compare it. Nomenclature is the other point you mentioned. But we need more of that, and perhaps next time that I meet with you people I could set up something like that in numbers. Twenty years ago, Mr. Ray Goertz was working with four-and-a-half percent compliance. A lot of people don't even know the definition of compliance. Therefore, we can't compare performance of the servo.

I will show you a few minutes of the film. I am happy with our own company's progress in this work. We are not doing just pure research work. We have our own separate profit and loss, and we are developing machines to use in industry (fig. 21). What we are doing here is trying to measure expected performance in carrying out a variety of tasks, not necessarily space tasks. We have some numbers and are measuring our ability to do a job with or without force feedback. What is suggested here is a couple of active manipulators for handling the satellite, and three passive tethered ones. We also use a copy of Ray Goertz's electromechanical wire-connect in doing this kind of measuring because we can take his machine, shut off force feedback, and do the job with and without force. The increase in efficiency in terms of power and time is surprising. We took Ray Goertz's manipulator and actually measured power to perform suggested tasks that might be done in space and we ran an average of around 20 watts. It goes up in the order of three to ten times without force feedback, not to mention the difference in time.

MR. ALLEN: May I interject here? There was a question brought up yesterday. I want you to note that on the manipulator doing the work, the working area is firmly attached to the manipulator by tethers. The stability of the entire system is controlled by an attitude control system which is

in the manipulator chassis. The manipulator operation is not worrying about maintaining position.

MR. MOSHER: Incidentally, we have a servo in our laboratory running now, and we are measuring performance. It is less than two percent compliance and position error, and of course the force ratio is quite high. There seems to be a lot of interest in this operation at the present meeting. Notice the depth perception through shadows.

You are talking about lining up the bolts, Mr. Diedrich; I don't know why you don't put force sensors on your manipulators and X and Y, then compare the forces, and if one is higher than the other, change the whole frame of reference of your reactor in the computer.

MR. DIEDRICH, Case Institute of Technology: We at the moment do not have any other sensor position on it.

CHAIRMAN JOHNSEN: You don't have the money, either.

MR. MOSHER: Force feedback is a valuable and subtle business. An example of this can provide some insight — the doorknob. When you open the door, you describe a specific geometric pattern, the arc of the circle. You couldn't do that with an imaginary doorknob. So it must be that it is a two-way street, the doorknob is telling the operator something. Whenever you are working in this euclidean world, where geometry is the rule, you must strive for specific geometric patterns. There is an opportunity in developing mechanism for space because we are getting out of the sea of gravity. It represents an opportunity, just as there was an opportunity when we climbed out of the ocean and started evolving new mechanisms for the body.

MR. WILLIAM ALLEN: I think one thing which doesn't show too clearly in the film is that they had one TV camera which could be positioned so that you had the overview and then could move the other TV camera to get a position and obtain essentially three-dimensional information out of the second camera, or greater resolution. In my terms, it is equivalent to having a camera on the end of your finger. You can stick it down real close and find out what's happening.

CHAIRMAN JOHNSEN: Can we see the rest of the film this afternoon?

MR. MOSHER: Yes, why don't you shut it off? I have a couple of essay papers. One is, "Exploring the Potential of a Quadruped," or this big walking truck (fig. 22). There are a lot of things to be learned from this work. I have a few papers left, more can be had, and the references show other work that has been done through the years. I will leave these on the table.

CHAIRMAN JOHNSEN: Thank you. I would like to get two more speakers from Europe because I think they have a mission here.

Mr. Mettetal is a consultant in foreign commerce for a Paris firm.

MR. J.C. METTETAL, S.I.E.R.S.: Ladies and gentlemen, for about 15 years, our company has been designing and producing different machines which are remotely controlled and work in a hostile environment, essentially in the nuclear field. More recently we have centered on power manipulators. When Mr. Johnsen explained his point of view about teleoperators and the new elements constituted by the humanoids in the Washington ANS Congress of November 1968, I took the liberty to tell him my own ideas concerning animaloids. It is to be noted that if he opened my eyes in what concerns those humanoids, maybe I presented him a complementary aspect in what concerns the animaloids from my Bible, Genesis, Chapter 2:18. "It is not good that the humanoid should be alone."

In his lecture Mr. Johnsen talked about a flying machine conceived by Leonardo da Vinci with flapping wings, more or less imitating the bat, and finally realized by Clement Ader with fixed wings. After Icarus and Leonardo da Vinci he practiced bionics, a science which is now becoming up-to-date in this country. The studies I personally made in the Natural History Museum in Paris, Department of Comparative Anatomy under Professor Anthony's direction, confirmed my keen interest in bionics. We examined and studied the vertebrate elements like snakes, tortoise neck, and invertebrate elements like elephant trunk, earthworm, and octopus tentacle. If man, instead of practicing passive comparative anatomy, practiced it in an active way, he would not only have noticed the particular morphology of the bat head but also tried to find out the reasons why, and immediately thought of radar. The humanoid could be the first step in the dynamic space separating man from his aim, following criteria perfectly described by Mr. Johnsen.

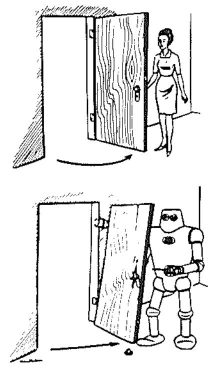

FIGURE 20.

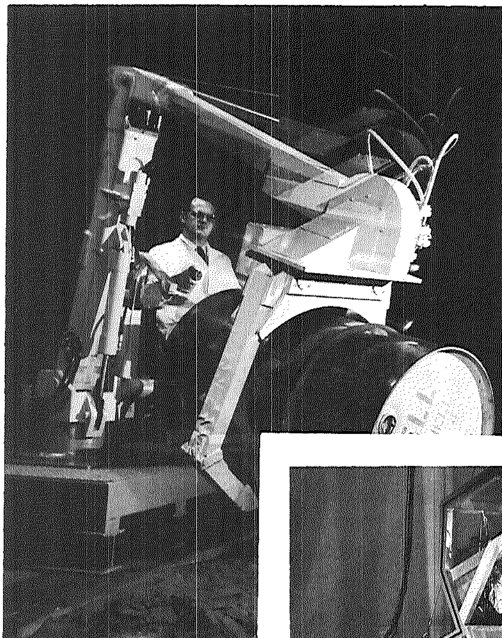

FIGURE 21.

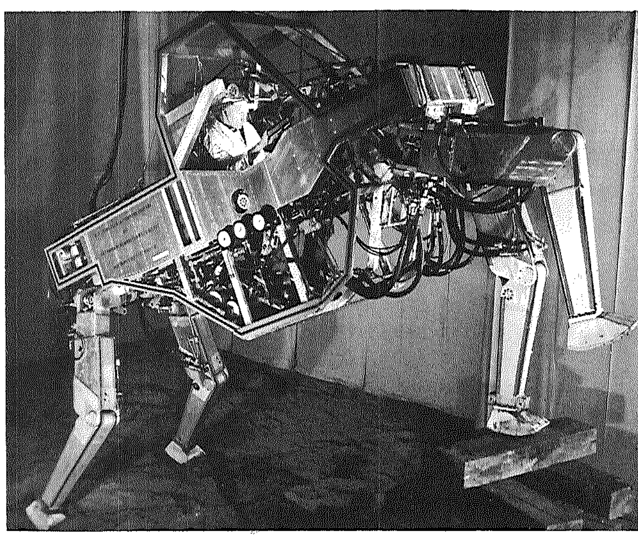

FIGURE 22.

On the other hand, man has always had on one side inert objects either for his habitation or for defense or attack (weapons), and on the other side living, active instruments either for his survival (meat, wool, and so on) or attack, defense, and draught (dogs, oxen, horses). When exploring or working in a hostile environment, one is in the presence of scientific, economic, sociological factors, and in fact, the last one should dominate the others. Before involving man in a hazardous exploration, he has to be replaced by efficient, reliable, economical teleoperators, and I think that the chain might be man, computer, humanoid, and animaloid. I will limit my examples to aquatic environment and moon conditions. In a fluid under pressure, almost opaque, which easily gets muddy, exploration and working are extremely difficult. Actually, people operate with the help of manipulators which are mechanically bound to a platform. It is nearly similar on the moon. Then self-acting machines could leave the platform — controlled or not — directly by man or through humanoids. However, this method may be too expensive.

I propose the "lost machine" method, which means the use of light, economical, specific exploration devices. Their possible loss would be of no consequence for the platform itself as it would be if an element bound to the platform got caught on a heavy external object. On the other hand, in the aquatic environment a heavy mass arriving near the bottom makes the water muddy and the other elements coming from the platform only make it worse. So I would propose:

First, an observing space humanoid with adequate senses, as sensitive as possible. For instance with computers which feed back sensations.

Second, the same thing with animaloids ejected and guided by aerial support, like short-range rockets. In the near future, total separation should be possible.

Third, according to the information received after the first and second phases, the presence, if necessary, of man replacing (or in any case being helped by) humanoids and animaloids.

In order to make this lecture as close to actuality as possible, let us say that bionics is already part of our lives for some up-to-date techniques. For instance, the

studies made about dolphins, particularly their epidermis. Our company did some research in a field I will just briefly describe. If you take a viper skeleton and manually assemble the different vertebrae, you notice that the assembly is flexible upwards and to the right and left, but not downwards, and that it does not disassemble by axial traction. Then, if you merely introduce soft bread at the bottom of the vertebrae concavities, you get an extraordinary phenomenon of flexibility similar to that of a live animal. On the other hand, let us observe that the brain controls sections of the spine composed of several vertebrae, groups of four or five at one time. Effectively, there are short or long muscles, generally twisted like our best cables, beginning on short or long sections.

Finally, the geometry of vertebrae differs according to the section concerned — front, middle, and back. Let us say that the middle part is composed of square vertebrae; the back part of rectangular, or rather, trapezoidal vertebrae; and the front part of their plates placed side by side for the flexibility of the neck. The ventral skin is provided with a system of thin plates. The animal can thus move on marble, but because of the structure of those plates it cannot move backwards.

The form of the vertebrae is different according to whether the animal is burrowing or strangling or adapting to several environments, such as earth and water. All vertebrae have side apophyses which prevent them from twisting, and we made very interesting radiographical studies and measures of periosteum hardness. On the other hand, the study of neutral fibers, centers of gravity, and bases of support enabled us to answer the biologists who were questioning the names of such-and-such nervous vascular system. Of course, we centered on the mechanical aspects of the mobility. From that we may project:

1. An economical machine adapted to its environment. In a system opened to environment (a fish has gills), adaptation to chemical phenomena, like corrosion, is feasible. There is also a weight advantage.

2. Remote control. The brain is on the platform, according to the chain man computer, humanoid animaloid. I will not specify the nature of computers needed. This animaloid must have different senses such as vision,

touch, and smell, beyond his own mobility. He must also have power, always adapted to the environment, solid or fluid. There are many kinds of transmission means. The technologist has to choose the simplest ones, taking as a pattern natural phenomena.

Under certain conditions it would be easier to let the vehicle home on the destination through means such as layers, luminescence, acoustics, radioactive source, and so on. The destination would then guide the object meant for its exploration or exploitation. So gentlemen, thank you for your attention and kind invitation.

CHAIRMAN JOHNSEN: Any questions? We haven't talked about animaloids before.

COL. BROWN: I'd like to make a comment. Mr. Mettetal spoke of the invertebrate concept, which hasn't been demonstrated, really, with these exoskeletons and articulated manipulators that have been devised. But if you take the concept of the elephant's trunk, this is really quite a different approach from positioning your terminal device, and I think it is one that probably has considerable promise.

CHAIRMAN JOHNSEN: I would like to answer that one. Down at La Jolla, in Scripps Institute of Oceanography, Dr. Anderson has been working on a manipulator using that concept — that is, all tension, flexible tension. It is made out of nylon and teflon so that it can operate in sea-water without suffering any degradation and corrosion. He is having a little trouble with it, but he's still working at it.

MR. ALLEN: There's a fellow at Stanford, also, building this type of gadget out of artificial muscles. He had one problem, according to Harry Erks — or Les Erks. Larry Laffner, I believe, is the fellow who did the work. He said he would need a computer about 200 miles long to control it.

MR. MOSHER: What bothers me is that there are so many pieces complicating the issue. I have a picture here of one and there are only six moving parts, three of them are segments and three are synchronizing links that hold them. You only lose the greater percent of your torque-transmitting capabilities when it's curved, compared with straight. There is a possibility of solving some of those problems. The thing here is, you can seal this completely with the belts,

you see, and there are other opportunities. You can drive this with a single actuator and whip it right around 360 degrees, 180 each way. You can also put actuators between links so you can get various curves, and there are other interesting combinations of that joint. This is something that could be used in space as well as an articulating finger.

DR. KOSOROK, Battelle-Northwest: I would just like to remind you some of us are working on animaloids.

CHAIRMAN JOHNSEN: Yes. Maybe you can just briefly mention what you are doing.

DR. KOSOROK: Yes. It is a continuing project in adaptive control studies. We are working on a computer controlled four-legged vehicle, a small pony size. We haven't really got a planned use for it, but it is an interesting concept for hostile environments. We have it under a real-time operating system so that we can do a lot of things with it very simply. We have quite a general interface and we can put a lot of sensors on the legs and determine pressures on the ground, forces we have from the ground, and equilibrium. These can then be fed into the computer program to adapt it to the environment.

MR. HAMILTON, Institute for Defense Analyses: I think we ought to at least mention the open-loop work that has been done on animaloids in Disneyland. If Mr. Mettetal hasn't seen that, he would find it interesting.

CHAIRMAN JOHNSEN: Thank you very much, Mr. Mettetal.

The colloquium resumed at 1:15 p.m., Chairman Johnsen presiding.

CHAIRMAN JOHNSEN: The first speaker this afternoon will be Mr. James Nevins.

MR. JAMES NEVINS, MIT: This afternoon I would like to discuss a supervisory type manipulator system and try to illustrate why we think development of this kind of system is justified. To begin with, the requirement that man must be capable of performing work in environments extremely hostile to him (hot labs, oceans, and space) has led to the development of machines or tools that allow him to be stationed in a friendly atmosphere yet perform work in the hostile environ-

ment. Historically, the AEC hot labs (ref. 1) have provided the largest impetus for the development of these devices, usually called manipulators. Of the family of manipulators developed, two principal classes are in common use. The first kind features master-slave control (ref. 2) in which the operator guides a model (larger than, or less than full scale) of the manipulator so that the remote slave will follow a specified path and come to rest at a specified point. These units are further classified (ref. 1) into unilateral and bilateral, depending on whether the operator received force-and-motion feedback from the remote slave. The second kind uses rate control, where the operator specifies the direction and speed with which the manipulator is to move, using a joy stick or a set of switches to activate the various degrees of freedom of the manipulator device.

Both techniques have been in general use in hot labs for approximately twenty years. The first kind has a load capacity of up to 50 pounds. The second kind has been extensively used in hot labs for handling all sorts of heavy jobs and is the only type presently being used or considered for undersea operations.

Recently another technique, called supervisory control, has been suggested. In supervisory control (refs. 3 and 4) (fig. 23), the operator specifies neither rates, nor paths, nor positions, but rather whole tasks, however primitive they may be, using a computer as an imput and control device. The pertinent features of the systems are as follows:

1. The manipulator is controlled by a local data processor assisted by sensors located at the task site; supervisory control by a human is provided at a remote location by hard lines or through telemetry.

2. Control of the system is based on determination of relative position vectors from a known reference to the desired task site (ref. 4) (fig. 24).

I will now try to illustrate why the present systems (master-slave or rate-control manipulator) even though they are relatively cheap are so slow and inefficient that a supervisory type manipulator system, as illustrated by figure 23, can be economically justified. Simply stated, what we are trying to do is put at the local site, the remote site, as much computer control as possible and enough local sensors so

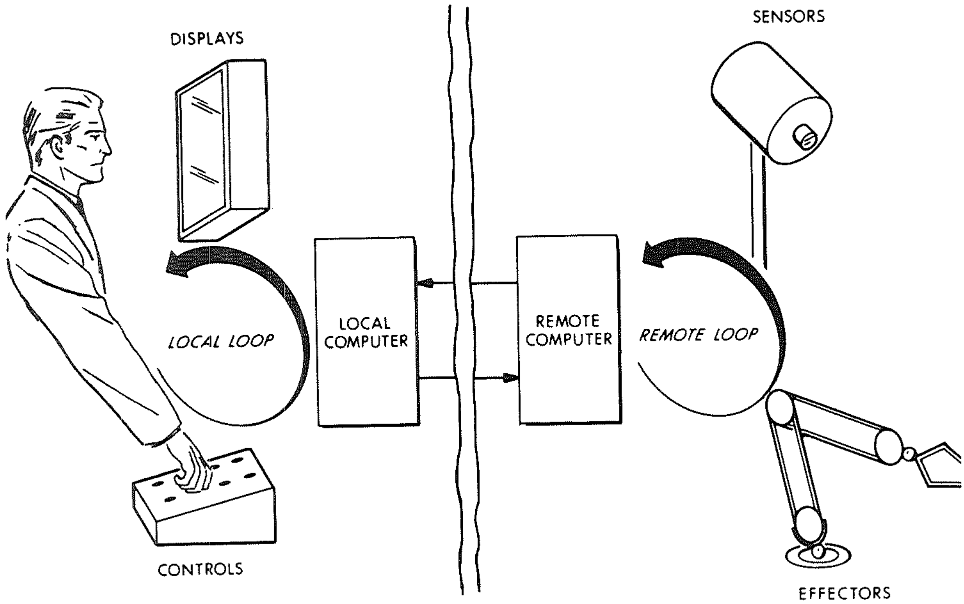

FIGURE 23.

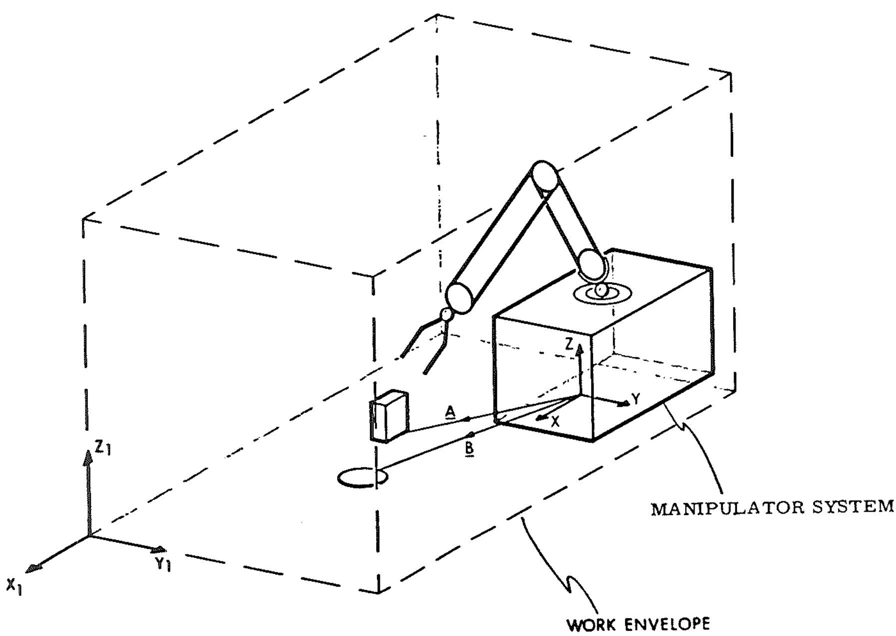

FIGURE 24.

we can perform significant levels of tasks. Where our technology breaks down, we plan to use man to pitch in and continue the task. All functions—pattern recognition, etc.—are under computer control. If man is used at all it would only be to monitor what's going on.

The two modes I wish to outline are as follows: in order to define the proposed manipulator it will be necessary to define the general manipulator task as illustrated by figure 24. The unit vectors x1, y1, and z1 define a three-dimensional work space. Attached to the right hand wall of this work space is a box, representing the manipulator system. Rigidly attached to the box is a multidegree-of-freedom manipulator. A computing coordinate frame, defined by the unit vectors x, y, and z, exists within the manipulator system. Mechanically aligned to this computing frame of reference are the manipulator and device for establishing pointing vectors between the computing frame and objects within the work space. Here, we must assume a peg and hole which are not round. The work task will thus be to see if the peg will, in fact, fit into the hole. The work sequence required is as follows: the manipulator must be positioned near enough to the peg so that the peg may be grasped and moved to the hole. Various orientations of the peg, with respect to the hole, will be used in testing to see if the peg fits the hole.

In order for the manipulator system to follow the above sequence, certain things must be known a priori or be capable of being measured — first, the locations of the peg and hole, with respect to the manipulator. Here we are defining two major modes of operation with respect to knowledge of subtarget location. In the first operational mode, the manipulator system would always be mechanically referenced to the work space. Thus, the location of the peg and hole in the work space, relative to the attachment point, would always be precisely the same, within some tolerance. This mode would be particularly useful for repetitive tasks at the same or different work sites, as with a computer-controlled milling machine. It also is obviously the fastest operating mode.

For this mode man's prime task would simply be to monitor that all was proceeding normally. In addition, if the system got itself into trouble he would have to devise the proper steps to get it back on line. This, by far, is the most efficient mode, but it requires a lot of computer storage. Of course, in the real case there are a lot of tasks you can't plan

ahead. You have to establish methods to do work and identify sites which have not been previously known. So the next thing we have to do is introduce some way of establishing pointing vectors, from our reference frame to the work site; that is, since we don't have known relationships between the two task sites and the computer reference frame, we will have to determine them. One method of doing so is to establish a relative position vector between the objects and the computing frame. (In figure 24 the vectors are A and B). Two things are required to mechanize this technique, namely: (a) the ability to discriminate between different kinds of objects in the work space and (b) a method of making the physical measurements associated with the pointing vector. If an optical system is used to establish the vectors A and B, then a visual monitoring system can be included. With the addition of such a system, any object in the work space may be selected, identified, and measured without benefit of a priori knowledge. This mode is paramount for nonscheduled activities such as repair. In addition, it is needed to perform tasks when the manipulator system is in the near vicinity of, but not mechanically referenced to, the work site.

Of course, to make this system work, subtargets must be identified and measured on the peg and the hole. These subtargets are necessary to define the orientation of objects in the computing frame, in order that the manipulator–approach orientation be proper for operating on the objects. If new objects of interest are similar to those of a stored set, then identification of subtargets will be similar, except for the scale factor, and therefore will permit standardized procedures to be employed. Use of subtargets also reduces the ambiguity resulting from viewing objects by two-dimensional techniques.

In the second operational mode, once the subtargets have been measured and stored, a simple command will correctly position the manipulator to grasp the object. Here the speed of response of the manipulator is limited only by the performance of the control loop local to the task. Another feature of this mode is the ability to stack tasks. For example, once the subtargets on the peg have been measured, the proper computer instruction would enable a computer routine to compute an optimal path from the present position of the manipulator to the desired position and could also enable the routine to position the manipulator, using the computed path.

We identify the fist mode as the semi-auto mode and the second as the hybrid mode. In addition we require the system to be capable of operating in either a master-slave or rate-control mode. A system requirement for these last two modes is made because it is anticipated that operating experience will be needed before it is possible to anticipate all the tasks that a system would be called on, particularly in the area of unplanned maintenance. Therefore, some basic mode such as a variable-rate mode would be needed for tasks where computer subroutines might not be available. Since the most serious constraining of the previous systems has been shown to be their slowness in performing tasks (refs. 2, 5, and 6), let us compare the system times to perform tasks using the time for a man to perform the task directly as the reference time illustrated by column 3 in figure 25. Four operating modes are listed in figure 25:

1. Semi-auto. This is the highest speed mode of the proposed system. In this mode the system is operating with large amounts of a priori information and requires minimum supervision. The expected speed of the system, compared to direct means, would be five to one-hundred-or-more times faster.

2. First level (hybrid). In this mode the system has a minimum of a priori data. It can stack tasks; therefore, it is expected that its relative speed would vary from twice as fast to as fast as the direct technique. The present hybrid mode speed is a guess. For the time being we have put it at a number of one to two. The advantage of the hybrid mode, of course, is that we can still function in a sort of semiautomatic mode once we have established the pointing vector. So it should be a fairly fast mode. How fast is, of course, open to speculation until the system performance for a range of specific tasks can actually be measured. In all probability the system speed should be higher than is presently being estimated.

3. Second level (M-S). The ratio of speed shown for the master-slave mode is the one recommended in references 2, 5, and 6 — namely, eight times slower than direct means.

4. Third level (rate). Again the speed ratio shown comes from reference 2— namely, one hundred times slower than direct.

To obtain a representative overall system efficiency where all modes might be employed, an arbitrary percentage of the total tasks was assigned to each mode in descending order (column 2 of figure 25). It is anticipated that the slowest modes would be required only for tasks that were simply never thought of in the original task evaluations.

The method of comparison follows. The percentage of the total time used, for each operating mode, is obtained by the product of the task-time/direct-time ratio and the percentage of the total tasks. The percent of total time is summed and compared to the direct means. Thus, the sum shown (48.8 percent) means that the representative division of tasks for the proposed system would be twice as fast as the direct technique. That is, if all the tasks were performed by direct means, the task-time/direct-time ratio would be one for all tasks and the percent of total time would of course equal 100 percent. As another example, suppose that the semi-auto mode task-time/direct-time ratio was only 1:5. Then the percent of total time, for the semi-auto mode, would be 16 percent and the new sum would be 64 percent. The proposed system would be about 1.5 times as fast as the direct technique.

The basic system principle is summarized by figure 25. Present manipulator systems operate in the region of 10 to 100 times slower than direct means. Only by using systems whose principal operating modes are much faster, and by pre-planning tasks to make maximum use of these high speed modes, will it ever be possible to efficiently perform work in hostile environments.

In order to demonstrate the system concepts just described, a proposal has been made to develop a working model. So that the emphasis may be placed on developing system concepts, it has been proposed to put together a "test bed" composed of hardware which, for the most part, has already been developed and is generally available. The test bed would be composed of two principal elements: (a) the principal units of an Apollo Block II Guidance, Navigation, and Control (GN and C) system for the CSM, and (b) one or more of the family of presently available manipulators (with modified interface).

The Apollo GN and C system (ref. 4) was designed to provide full on-board capability for guidance, navigation, and control for the manned Apollo vehicles, during the mission phases of orbit, maneuver, rendezvous, lunar landing and

ascent, midcourse maneuvers, reentry into the earth's atmosphere, and earth landing. Optical force and attitude measurements of high precision are used by the on-board data processor to control these activities. Digital programs directly control and stabilize the vehicle through the reaction control systems and start, stop, and throttle the vehicle propulsion systems.

This system, except for subtarget distance sensors and a remote visual monitor, contains all the basic measuring elements referred to earlier. It also includes a large data processor with a flexible input-output format. Sensors for determining target range and range rate (at close distances — 1 to 10 meters), and a remote visual monitor would need to be integrated with the system. Accurate target ranging techniques for close distances have been developed and studied at the Instrumentation Laboratory (fig. 26) (ref. 7). With this technique (fig. 26) it is expected that we can establish the direction and the distance accurately — accurately in this case would be in the order of thirty thousandths of an inch in 10 feet.

I would like to comment on time delays associated with present communication systems for space operations. One test I performed when a 501-booster was sitting on the launch pad was to measure the time delay associated with activation of a single discrete event to the airborne computer located in the command module. The round trip from Mission Control Center in Houston, through the control-center computer, over the ground lines to Cape Kennedy, through the rf links at the Cape to the booster, and then back through the same route was 8 seconds. Discussions with the communications people at Mission Control indicate that delays can be pulled down to about 5 or 6 seconds. (Note: These modifications were made sometime last year.) Of course, transmission delay associated with this test was minimal. In lunar orbit we would have to add the 2.5 seconds in the transmission delay for the round-trip time. For analog-type signals the delays go up to about 18 seconds or longer, again without space transmission delays.

That will end it.

CHAIRMAN JOHNSEN: Any comments or questions?

MR. FLATAU: Could you be more specific about how communication delays are introduced?

OPERATING MODE	% TOTAL TASKS	(TASK TIME / DIRECT TIME)	% TOTAL TIME
SEMI-AUTO	80	1/100	0.8
1ST LEVEL (HYBRID)	18	1/2	9.0
2ND LEVEL (M/S)	1.75	8/1	14.0
3RD LEVEL (RATE)	0.25	100/1	25.0
	100		48.8

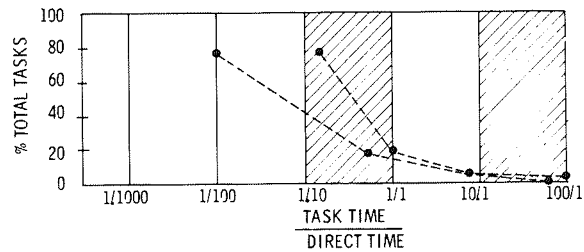

FIGURE 25.

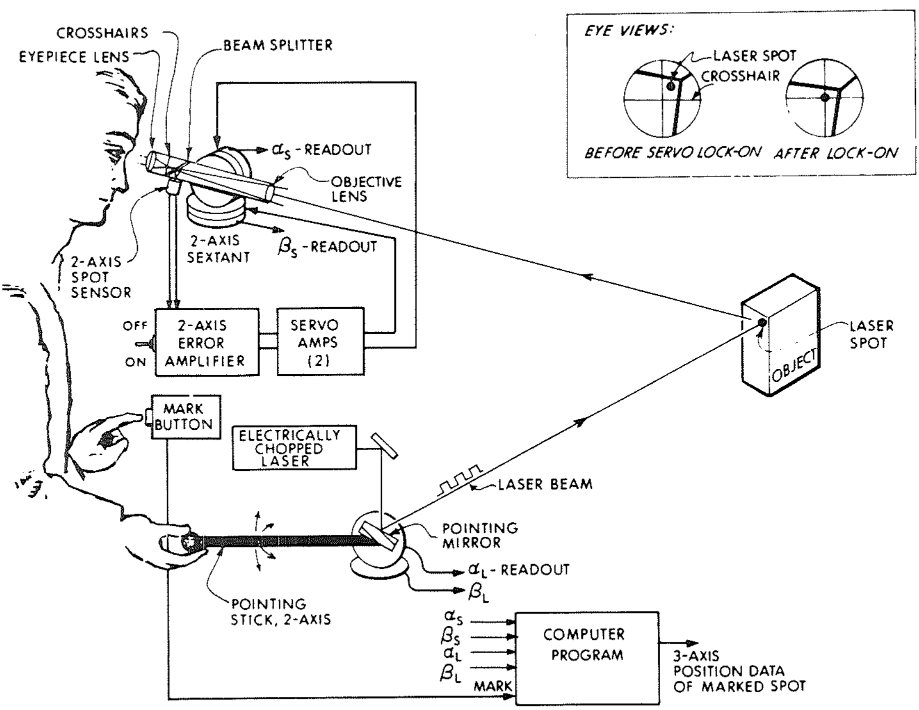

FIGURE 26.

MR. NEVINS: Between the spacecraft and the ground there is a command link with a maximum capability of 1000 bits per second. A command word consists of 22 bits of which 7 bits are the vehicle and system identification and 15 bits are the data. For the Apollo airborne computer the 15 bits of data are actually three 5-bit words where the first and third words are the same data and the second word is the one's complement of the same 5-bit word. Besides this redundancy the entire command word is encoded into a 5-bit Barker code. Thus, the command word instead of being 22 bits long is now (5 x 22) or 110 bits long. In addition, during the transmission of the data, three data-validation loops are used. The validation loops are the ones at the Command Site, the Remote Site, and the Telemetry Command Verification Site. These loops all work serially; that is, data cannot proceed from one loop to the next loop until the data has been transmitted, received, checked, and a validation pulse sent back to the next lower loop. Also, the same data is nominally repeated three times before being finally accepted as correct. In addition to delays caused by encoding techniques and validation loops, there are delays caused by processors on the ground in assembling and formating the data.

MR. FLATAU: However, if you wanted to use more bandwidth, you could cut this down enormously.

MR. NEVINS: The point to remember is that the available system and facilities are very extensive and would cost a great deal to modify. The system puts heavy emphasis on reliability, hence, must have appreciable processing delays. These delays can be reduced but the reliability will go down. That is, the controllers want to be able to command the spacecraft to do something and have it respond in the presence of noise or what have you. It is a system from which it would not be reasonable to expect radical changes for a number of years. One reference* is listed; others I am sure are available through the Manned Spacecraft Center.

MR. MOSHER: Do you have a publication on this work?

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*Apollo Command Telemetry Control Capabilities Study — Final Report (Preliminary), Philco-Ford Corporation under NASA Contract No. NAS9-1261. Report No. PHO-TR 290, 10 February 1967.

MR. NEVINS: We have a paper which we sent around to a few people. We have not yet published it formally. In addition, we do have some thesis work which has been concerned with the optimal control laws for moving an arm from one location in space to another and the determination of the minimum number of degrees of freedom to accomplish certain tasks. Additional thesis work is planned for development of a "pointing system" for identifying and locating objects accurately in the work space with respect to the computer reference frame.

CHAIRMAN JOHNSEN: Has anybody there done any analyses? Take, for instance, the submarine. The cost of stay time of the submarine, you know, is quite high. Have you done a cost-effectiveness analysis of what something like this would do in terms of money?

MR. NEVINS: Unfortunately not. In fact, the prime reason for generating the data in figure 25 was to try to encourage that kind of study. Not until we look at the cost of using these inefficient manipulators can we demonstrate the requirements for a computer-driven, man-supervised manipulator. Discussions with the Alvin people, who are involved with doing things on the ocean floor (2000 feet) with a rate-driven manipulator, point up how slow and tedious it is to do even the simplest kind of task with these manipulators. Up to now this kind of message has not got back into the design loop to encourage people to work on better manipulators.

MR. FLATAU: What is the origin of the first two numbers mentioned earlier — the task-time/direct-time ratios for the semi-auto and the first level (hybrid) mode.

MR. NEVINS: The task/direct-time ratio for the semi-auto mode comes from automatic milling machine techniques. This number assumes that you have got a "hard" mechanical reference, one accurate enough to do a complete sequence of tasks from *a priori* data at maximum speed.

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7. Figure 26 — Three-Axis, Spot-Designator System is from an unpublished report by H. Seward of MIT/IL.

CHAIRMAN JOHNSEN: Any more questions. Thank you very much, Mr. Nevins.

Norman Diedrich is our next speaker.

MR. NORMAN F. DIEDRICH, Case Western Reserve University: Over the last three years, maybe four now, we have been developing facilities at Case in the Digital Systems Laboratory for evaluating the feasibility of using a small general-purpose computer for controlling a remote manipulator. The particular manipulator we have would probably be in the class of a rate-control manipulator. The initial rate control was two-step, two-speed, each direction on five degrees of freedom. It has been modified to give us seven degrees proportional control, as will be further explained with the film. Concurrent with this development, a series of algorithms was developed to permit the use of the computer as an interface between the operator and the manipulator. The goal of these studies was threefold: first, to indicate further steps to improve the man-machine communication of this teleoperator system; second, to obtain a maximum manipulator flexibility by reducing the number of operations that were required of the operator; third, to reduce operator fatigue. Based on the work that has been done to date, it was decided that this computer teleoperator system was feasible, and the next stage would be to use the system to perform an actual task. Such a

task, mainly guided by our support, was selected from the Space Nuclear Propulsion Office — assembly of a mockup nuclear reactor. Reduction of operator fatigue was expected to be very noticeable.

I think at this point we will show the film. (Also, see slide (fig. 27).

CHAIRMAN JOHNSEN: Are there any questions?

QUESTION: Do you control the computer or the specific geometric patterns describing particular paths for the end of the hand?

MR. DIEDRICH: In this particular case, and in most cases, the end point is specified, and the move between end points is determined.

QUESTION: What happens if your programmed direction of pull, let's say of those control rods, is at a one-degree angle with the actual orientation of the rod? What would you do about that?

MR. DIEDRICH: If it is slightly cocked, we can do it. Damping rods would be needed — we'd have to have some kind of a lead in the hole where the rod comes through the upper plate.

QUESTION: Do you foresee there would be some feedback during the programmed operation that senses there is a misalignment and re-programs itself?

MR. DIEDRICH: Currently we don't have any force feedback on the device, so the only way this problem could be recognized would be if the operator saw the thing was dragging on one side. One of the modifications currently in process is to provide for the operator to manually override one axis, for example, while the computer is still running the basic operation. This might come in handy if the damping rod was a little bit out of line because the operator could then trim that position without really taking the whole operation over to himself.

QUESTION: It looks like in reassembling, for example, it might be very difficult to pick up a nut.

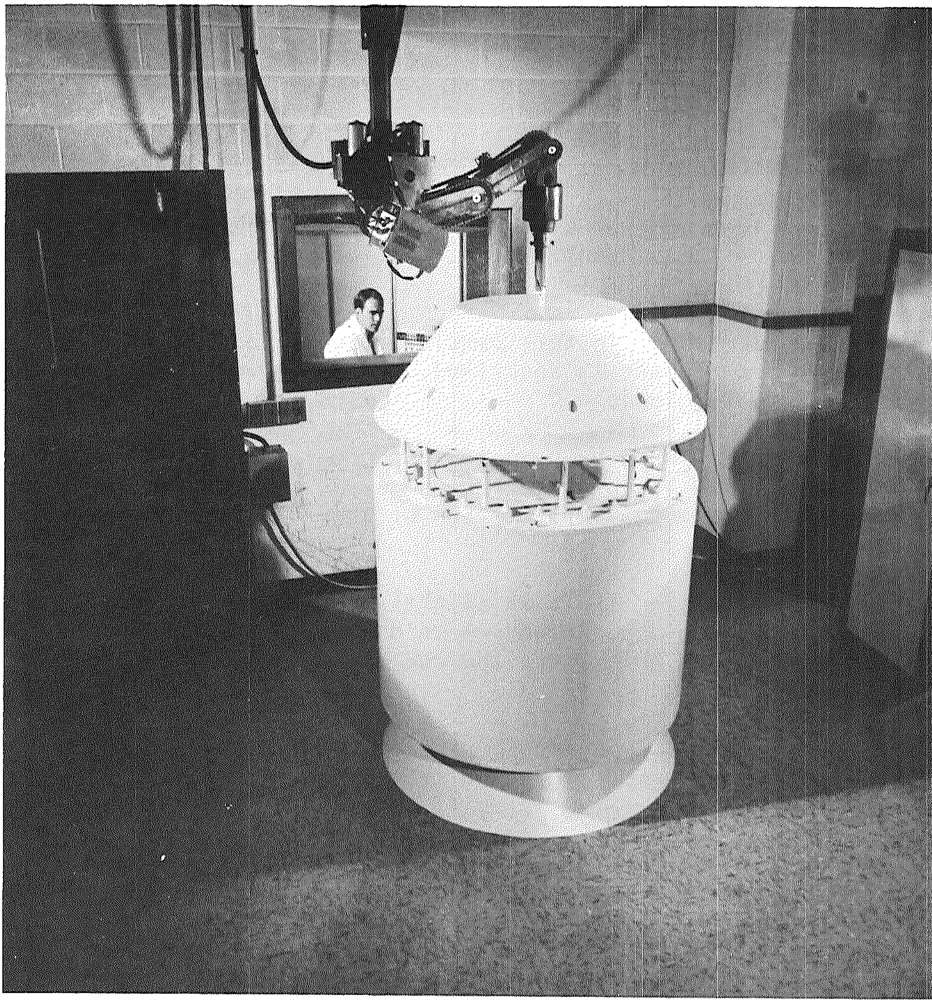


FIGURE 27.

MR. DIEDRICH: It would be. I have not addressed myself to the problem of reassembling.

CHAIRMAN JOHNSEN: I think perhaps this is the business of tooling. There are some people here who have been working in this area.

MR. FLATAU: I notice several terminal device changes have been made. Were these done manually?

MR. DIEDRICH: Yes, they were done manually. We have a fixture for doing it automatically, which hasn't been programmed, but it doesn't appear to present any problem. The tool-changing fixtures were part of the original equipment supplied by General Mills.

MR. FLATAU: How did you pick up the "hex" position of the nut. Was that computer controlled?

MR. DIEDRICH: No. The wrist rotation and the opening and closing of the hand, at the time this film was taken, was entirely open loop. As far as indexing on the nuts, I would set down so that there would be a slight free load and turn it until it indexed, and that's why it was done in the sequence of turning-lifting motions. The modifications necessary to get the rotation and the hand opening-closing are in process right now.

QUESTION: "Step" motors?

MR. DIEDRICH: No. The motors used on this are all of the universal type, gear motors. The ones for the hand opening-closing and for wrist rotation are probably 20 hp, or something on that order — 5000 to 10,000 rpm. The motors used for the basic arm motions are one-tenth hp and the remaining motors are one-fifteenth, all running on 120 volts.

CHAIRMAN JOHNSEN: I think we ought to point out that the reason why this particular manipulator was used is because it was surplus and available.

MR. DIEDRICH: And cheap.

CHAIRMAN JOHNSEN: That was the governing factor. We were primarily interested in determining feasibility rather than developing sophisticated hardware.

QUESTION: Within what tolerances have you had to position the object you are working on?

MR. DIEDRICH: The basic tolerances I have had have been within the range of this machine. In other words, if I go to pick up the end belt, for example, I can get within an eighth of an inch or so, and that's fine as long as I lift straight up. It would appear that the best way to do this sort of thing is to make sure that the alignment for something on that order is right along with the axis.

MR. MOSHER: You orient your computer image of the reactor to go anywhere the computer finds it?

MR. DIEDRICH: Yes.

QUESTION: In this type of application, did you compute the location of all the nuts and just direct from one to the other, or did you have to use the television camera?

MR. DIEDRICH: Using the keyboard, I went through and directed the manipulator to the various points, and then recorded those moves for filming, because you like to be able to repeat things. The time required for the keyboard entry would have made the motions prohibitively slow. The software is not written at the moment because there are hardware modifications in process and I didn't want to rewrite all the software.

CHAIRMAN JOHNSEN: Thank you very much Mr. Diedrich. I would like now to ask Ray Goertz to discuss two kinds of work that he has been doing. You all know that he has been one of the long-time leading lights in manipulators, particularly master-slave manipulators. He has also done a considerable amount of work on head-control television, which I think is a very important technique for having good visual control of what you are doing, especially in a remote environment. I think Mr. Goertz is going to combine both topics in his one discussion.

MR. RAY GOERTZ, Argonne National Laboratory: Thank you. Yes, I certainly will combine the topics of remote viewing and manipulation. These two items, and others, are essential parts of almost all remotely controlled general-purpose manipulator systems. I learned this some 20 years ago. We built our first master-slave manipulator before we had developed shielding windows. We tried using this early

manipulator with periscopes, mirrors, and with direct viewing through air. The former slowed down the rate at which work could be done compared to that which could be done with the manipulator while viewing directly. This stimulated us to start developing large shielding windows that would be optically and economically acceptable. As most of you know, this development, along with the development of more advanced master-slave manipulators, has been successful. This system is used in most hot facilities in the free world.

In recent years we have worked on developing electric master-slave manipulators and slave television. This system allows the slave arms and TV camera to be moved freely because only electric cables connect the master arms and TV monitor to the slave arms and camera. We could replace the electric cables with radio transmitters and receivers which have appropriate modulators and demodulators.

The main objective because of the radiation hazard has been to develop techniques and devices that provide a means of carrying out complex experiments and other operations remotely. The aim has always been to do the work more quickly and more economically. Before general-purpose manipulators were developed, it was necessary to design and build new specific-purpose, remotely controlled apparatus for each new experiment. This proved costly and time consuming.

Let us take a close look at the economics of remote handling and manipulating intensely radioactive materials. Handling devices some 22 years ago were mainly tongs, cranes, and a couple of very crude unilateral manipulators. There were no windows, a few poor periscopes, and no TV. We first developed two unilateral electric manipulators and these became the forerunners for the General Mills and PAR unilateral manipulators. In less than a year, we had decided that the unilateral manipulator had serious technical and economic shortcomings. Only one or two of the seven motions could be operated at one time. Because of these limitations and others, we stopped developing this type and switched to the approach of mimicking the basic motions of the human hand and arm. Each manipulator would be controlled by one hand of the operator. Economically this was a good choice.

There are now over 1000 pairs of master-slaves with their shielding windows in use in the U.S.A. We estimate that they are actually used about 20 percent of the time for one shift. The cost to operate them is at least $10/hr

counting radiation safety and supervision. This all adds up to 4 million dollars per year. Had the master-slave system not been developed, we might assume that all the work would be done with unilateral electric manipulators. Tests have shown that it takes over 10 times as long to do tasks with unilaterals as it does with master-slaves. Therefore, the yearly cost would be 40 million dollars per year. The annual operating saving is 36 million dollars. On top of this, more hot facilities would be needed. The investment to develop all of the mechanical master-slaves, the electric master-slaves, the shielding windows, some TV, etc. has added up to only about 6 million dollars for the 22 years.

Manipulator systems are simple in their requirements and objectives (fig. 28). They extend the manipulative functions of hands and arms and reflect back to the operator the necessary senses of feel. The viewing part of the system extends the necessary image information back to the operator. Although the basic needs can be stated simply, it is not so easy to develop and build good systems. Fortunately, nature permits us to develop the systems in steps and come up with very useful devices that are moderately simple but fall far short of the longer-range objectives and needs. As an example, one of the most widely used systems is a pair of mechanical master-slaves and a shielding window. This system performs quite well but carries out simple tasks at only about 1/10th the rate of working directly with the hands. Also, the work area is limited in size and location because the window and arms are anchored to the shielding wall.

These manipulators have only seven independent motions and can be operated to apply any force or torque to a solid object. Since a solid object is limited to six independent degrees of freedom of motion in space, the manipulator need have only a similar set plus a method of attaching itself to the object. The most versatile method is to provide a seventh motion for grasping the object. Additional motions can provide operation of additional fingers and for additional arm movements. Force reflection from the object back to the operator is very important for a number of reasons. It helps avoid exerting unwanted forces on the object, helps movements when other objects are near and might cause a collision, and provides a means for the object to determine the path of motion for some operations.

Moving a lever is one example of the need for motion and force feedback to the operator and for the entire manip-

ulator to be bilateral in its motion behavior. This allows the slave to follow the path dictated by the lever with only moderate forces in any undesirable direction (fig. 29). On the other hand, with a unilateral manipulator (where the controls produce a velocity) great care must be taken to avoid high forces. This slows the rate at which work can be done to 1/10th that of master-slaves, on the average.

Another example is fitting one part into a fixed part (fig. 30). As the part is moved into place, some of its degrees of freedom are lost.

We believe that manipulators can be made large enough to handle very large loads but the size should be more dependent on the overall economics than on the engineering feasibility. It is probably more economical to provide manipulators having moderate load capacities that will handle most of the work, and then use cranes for the loads above the 100-pound capacity of the manipulators. One goal is to develop an electric master-slave having the general capabilities of the human arm and hand. This slide (fig. 31) shows the latest manipulator developed at Argonne — the Electric Master-Slave, Mark E4A. It has a load capacity of 50 pounds in any direction and has force reflection and other master-slave characteristics similar to the well known Model-8 mechanical master-slave. The feel is not quite as good as the mechanicals because of the motor inertias and some additional friction. However, since it can approach the work from almost any direction, has force boost, brakes, and other features, its overall performance is judged to be considerably better than the mechanicals even if each could adequately cover the work volume of interest. Since the slave arms can also cover much larger volumes, its usefulness is far greater than that of the mechanical master-slaves for large facilities.

All the motors, except the X-drive, are mounted in a group on a body that is fixed to its support device. This method avoids the inertia that would be included as part of the arm mass if the motors moved bodily with any of the motions of the arm. The method also avoids cascading of the force-reflecting servos.

At present I am developing a very high-performance, moving-coil dc motor for use in future electric master-slave manipulators. It is designed to reflect an equivalent mass of less than 2 pounds in a slave arm having a load capacity

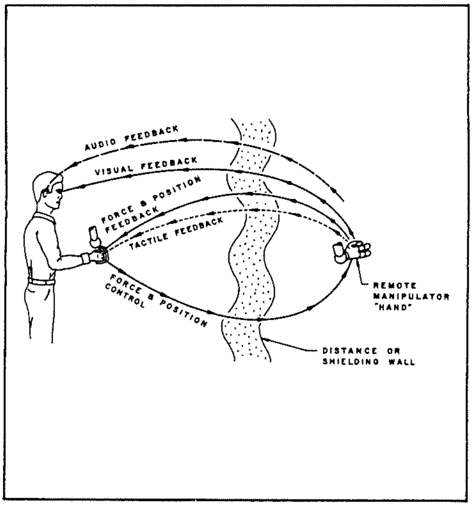


FIGURE 28.

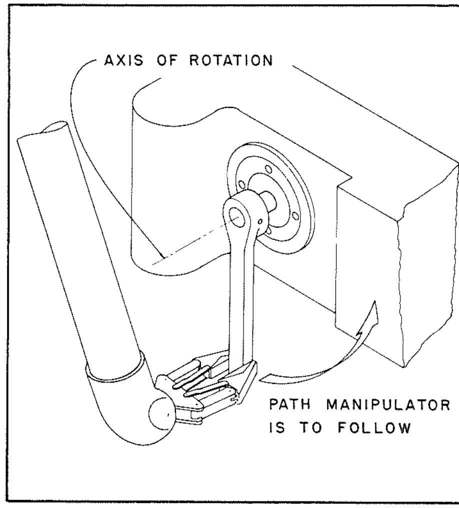


FIGURE 29.

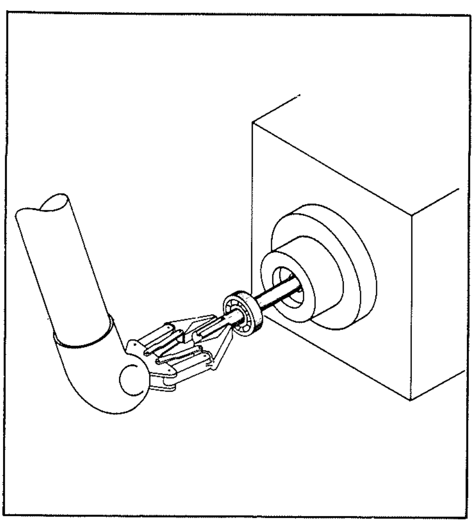


FIGURE 30.

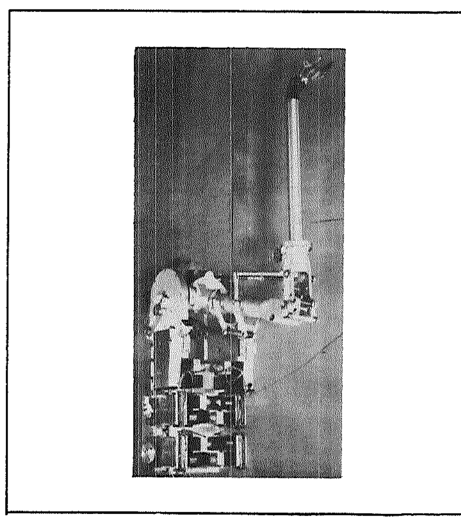


FIGURE 31.

of 100 pounds. At the same time the maximum heat generated in the armature is to be no greater than 100 watts. The primary objectives are to increase the sense of feel and reduce the cooling problem. This motor will have a very short mechanical time constant and an even shorter electrical time constant. Consequently, stable force feedback can be used to further improve feel by reducing the apparent inertia, friction, and other factors. Since the economic factor is the underlying reason for developing better manipulator systems, it is important to improve the rate of doing work and to expand its versatility. Both of these will be improved as the feel is improved.

There is always a question as to which parameters to emphasize in the next developments. One factor is certain, the master-slave system for the arms and television is the best of any I have studied or heard of (fig. 32). It extends the hands and eyes to a remote hazardous area and, thus, the great dexterity of man can be brought to bear on a distant task. As these systems are developed to higher perfection, they will be able to more accurately transmit and feed back information almost exactly as if man were in the hazardous area himself. These advanced systems will also be easier to operate. Thus, operators with different skills can perform operations remotely even though they may have little training.

The choice as to which parameter to stress at a given time within the master-slave system is a little difficult. It depends on the funding level for development, existing technology, characteristics that potential users think they need, etc. The needs for advanced systems exist now, but there is a lack of understanding of the economic advantages by facility designers and operators.

The approach to the development program, in my opinion, is to carry out more or less continuous development on components and subsystems and also to reduce to practice at intervals of two to three years a complete system of prototype models. Each new manipulator system would have significant improvements in at least one important parameter. Also, each complete system would be a very useful device. The arm sizes and load capacities should span a large range of at least 1000 to 1. Improved slave TV would be an integral part of each system.

Before long, a manipulator system should be developed that has the size and shape of man. The load capacity and dexterity should approximate that of man for such tasks as repairing machinery. This slave man should be able to walk and climb in and over all places that man could go in a reactor plant or process plant if no radioactivity were present. The visual part of the system would be high-quality slave TV. Walking and climbing would be on two, four, or six legs. This slave man would be useful in facilities that were not designed for remote repair and therefore have no manipulator support systems. Although the cost of developing a good electromechanical slave man would be high, this cost would be returned many fold in the next fifteen years. It might come down to where it could be economically used as the chief repair device for new reactor facilities.

Also, smaller walking and climbing manipulator systems should be developed for inspection and instrument repair in small hot areas. One of these might be the size of a cat and be able to climb or crawl through pipes, around vessels, etc.

Television pictures are much inferior to direct view through a window at a moderate or close distance. There are several reasons for this deficiency. The number of discrete elements of lightness or darkness in one picture is only a small fraction of the number presented to the eye through a shielding window or good periscope. Also, television has a low dynamic range of brightness-to-darkness ratio of only about 100 to 1. This makes it almost impossible to get a good picture of machinery with poorly illuminated recesses. Besides, stereo has never been developed to a fully satisfactory degree.

It is possible to improve the effectiveness of a TV chain without improving the TV itself. One method is to narrow the angle of view so that the total picture elements are concentrated on a moderately small scene. This narrow angle of view can be aimed to move from one scene to another. We have done this by "servoing" the camera and monitor to follow the pan and tilt motions of the operator's head. The face of the monitor stays at about two feet from the operator's eyes and swings in arcs with its face always nearly normal to the operator's line of sight. The TV camera is also servo driven in synchronism with the pan and tilt motions of the operator's head. This system shows great improvement over TV used with a wide-angle lens or when only

the camera is aimed. Also, it is moderately easy to operate. We found that we had to put a "dead spot" in the servos to prevent the continual small angular movements of the head from blurring the picture. In addition, the narrow angle of view requires some learning. This slave-TV system gave good enough performance for us to recommend it for use in a master-slave manipulator system.

With an angle of view of 30 degrees, most of the items are in the whole work area and may require 150 degrees or more. After a while the operator remembers where most of the items are located and can perform manipulations with reasonably good speed. He will have to search for some items occasionally. We judge this slave-TV viewing system to be about as good as a window when the distance to the work is 12 to 15 feet.

Although this head-controlled TV is the only one that we know of that was designed and tested as an integral part of a master-slave manipulator system, there are others that have been developed for other uses such as military observation and tracking. As a further improvement in the arrangement of television for use in a manipulator system, we have considered using two TV chains. One would provide a reasonably good picture covering a moderately small angle of about 15 degrees. The second TV chain would provide a wide-angle picture surrounding the small one but be blanked off the small picture. Each would have the same magnification. John Chatten has tested this arrangement for target tracking and other observations. It works quite well. With some modification, this basic arrangement should give reasonably good results for master-slave manipulator systems. Of course many other improvements are also needed.

Other viewing screens could be used instead of the CRT monitor. Projection onto a hollow hemisphere screen has been considered and some organizations have mounted small CRTs on the operator's head.

The common definition of line resolution of a TV chain is misleading because the monitor is not required to faithfully reproduce the details of the lines seen by the camera. When sharp high-contrast lines are the scene for the camera, the monitor need only barely show that the lines exist and the contrast may just be discernible. Thus an 800-line chain may only reproduce up to about 150 lines sharply. Even then, the contrast will likely be considerably below that on

the test pattern scene (fig. 33). Clearly, TV itself needs to be greatly improved if we are to be able to view remotely as clearly as we can locally.

This movie shows some of the work done for NASA by the Argonne National Lab. We carried out a short study of possible uses of manipulators for space work. A task board was furnished by NASA which has various screws, pipe connectors, electrical connectors, etc. Work was done on the task board under the following four conditions:

1. Subject working directly while in ordinary clothing. Working time: 7 min.

2. Subject working directly while in an Apollo state-of-the-art suit pressurized to 3.5 psig. Working time: 20 min.

3. Subject working with Model M8 master-slave manipulators while in ordinary clothing. Working time: 25 min.

4. Subject working with Model M8 master-slave manipulators while in a Apollo state-of-the-art suit pressurized to 3.5 psig. Working time: task could not be completed because of operator fatigue.

The Apollo suit is not a constant-volume type and this means that the person in it must do work to move the arms, legs, and fingers. The glove on this suit is very stiff when pressurized, and it is quite difficult and tiring to grasp things. It is especially difficult to grasp the handles of the manipulators.

In addition to working the task board, we tried using the manipulators to dock with a couple of objects. The first object was a 50-pound oscilloscope moving toward the manipulators at 5 or 10 in./sec and rotating at about 20 degrees per sec. There was no trouble in catching and gently stopping the oscilloscope. The other object was a 120-pound beam similarly moving toward the manipulators. Again, docking was extremely easy. From this we believe that master-slave manipulators could be used for docking with objects in space that are not equipped with docking rings.

The latest electric master-slave manipulator developed at Argonne is shown performing a variety of tasks. It has

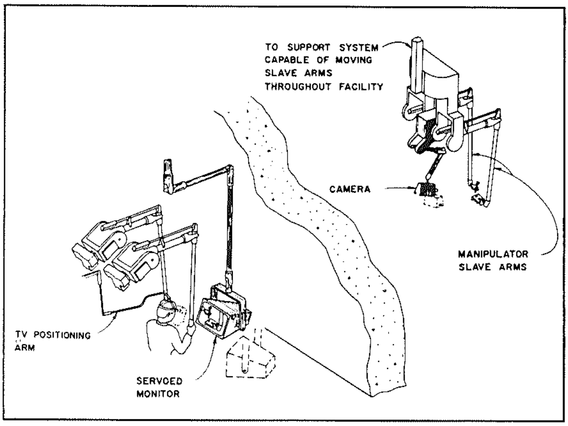


FIGURE 32.

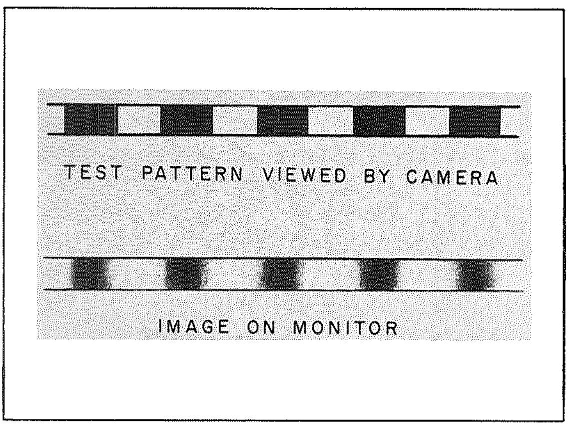


FIGURE 33.

three different selectable force ratios: 1 to 1, 2 to 1, and 5 to 1. Force reflection and reversible or bilateral motion are good for all force ratios. The movie also shows an experimental 5-motion, head-controlled TV system. The extra three translational motions over and above the pan and tilt helped considerably in carrying out manipulations. For example, moving the head from side to side gave depth information to the operator. It also allowed him to get different viewpoints. When the operator wanted a closer view, he had only to step forward.

In closing, I would like to reiterate my opinion that the strongest reason for developing better manipulator systems is to increase the efficiency of operation in hot facilities, to improve their plant availability, and to reduce their design and construction costs. These general economic reasons also apply equally well for space and underwater uses of advanced general-purpose manipulator systems.

The rate and versatility applied to work are the keys to high economy. The master-slave type of arms and TV is the fastest and most versatile of any system so far developed. Yet, to date, the master-slave potential has only been scratched. The time will come when remote work can be done as rapidly and surely as it can with the hands. It may be possible to actually increase the remote rate above that of direct. Computers can help in certain subroutines, but it will likely be a long time before they can even begin to have the dexterity, skill, versatility, etc., of the human hand, eyes, and brain. However, for very distant operations where time delay is significant, various kinds of computers will be needed. Otherwise the rate of doing work must be very slow.

CHAIRMAN JOHNSEN: Before we have some questions, I want to point out, the P.A.R., who make the rectilinear manipulators, were going to be here. At the last minute I guess something happened and they couldn't send a man along. I want to point this out, because I don't want to give you any impression that I have a bias towards master-slaves. Let's have some questions and discussions on Mr. Goertz's presentation.

MR. FLATAU: Two questions. We did very little work on TV viewing, but we found one thing when we had a very narrow angle of view —one tended to lose the slave arms out of the

area of view and couldn't get them back in. Did you find anything wrong with your view?

MR. GOERTZ: Yes, inexperienced operators tend to "lose" the slave arms. The method that works best is to find the slave arm by moving the head and then move the arm to the desired location while following it with the slave TV.

MR. FLATAU: Did you check what the additional hindrance factor was by having a man in a space suit work these tests rather than the man doing it directly by a manipulator?

MR. GOERTZ: It took about the same length of time.

QUESTION: Mr. Goertz, could the man have completed the task in the space suit working directly on the problem?

MR. GOERTZ: Yes, he could, and he did. He did this in about three times the time it took him to do it in his shirt sleeves directly, but he was much more tired.

COL. BROWN: With the head-control TV system, did the operator's concentration and efficiency, and thereby tolerance, decrease steadily with time?

MR. GOERTZ: We have not tested people long enough to find that out. We don't know. We did find out that the people, when they first tried to use it, were quite tense. After a few hours, off and on, they were much more relaxed.

COL. BROWN: Would the field of view influence that?

MR. GOERTZ: I think it might have.

MR. JOHN CHATTEN, Control Data Corporation: I wanted to comment on your statement earlier that NASA felt it wasn't necessary to redesign equipment to let the awkward manipulator handle it. That policy may change. We have been studying many problems of maintainability. The work may have to be done in a space suit. It turns out that the clearances, the size, the grip, and all this, match very closely what you need for a manipulator. In addition, in other studies, some of which are going on now, the people who put this equipment together have pointed out when we go out to get this information, that "If you could just build it the way you're talking about, we can maintain it; we can

check it out much easier than we can now." So I think in the forthcoming generations that the equipment being designed for man's use may also be readily usable by a manipulator.

MR. GOERTZ: I think that's a good point. They limited us for this particular study.

MR. CHATTEN: To clarify my last question, there are four possible ways of doing the task of the space suit and the manipulators, and directly. One is man doing the task directly in his shirt sleeves; using the manipulator; directly in the space suit; and in the space suit using the manipulators. Did you cover all four possibilities and could you arrange them in order by difficulty?

MR. GOERTZ: Yes, all four were tried. The last one you mentioned, the space suit with manipulator, was by far the most difficult. The operator got so tired he could not finish it.

MR. FLATAU: What was the fatigue effect?

MR. GOERTZ: We don't know. We had only a day or two to do it. My observation of the people who did it was that the fatigue factor was higher in the space suit even though the subject was working with the tools and gadgets directly with his gloved hands.

MR. JAMES JONES: I would like to comment in defense of the suits. The state-of-the-art suits offer torques and essentially complete balance, and gloves are being developed with counterbalances so you don't have as much of a problem, and hopefully, it won't be quite so bad in the future.

MR. GOERTZ: Yes.

QUESTION: With these better suits that are coming up, would you envision changing the interface between the master-slave and man such that maybe the controls are inside the environment of the suit, coming up with a special glove just for that?

MR. GOERTZ? Yes, I think there is a possibility of putting a handle inside by removing the hand from the glove and moving it into another area.

COMMENT: I was thinking in terms of having direct skin contact with the control but with only the hand encapsulated.

MR. GOERTZ: Yes. That is what I had in mind.

MR. FLATAU: I would like to comment on a concept I had, which I am not sure would work. Maybe some of the laboratory control people, if they are here, can give me an idea (having built a master for a slave) whether I could do away with the master. That is, if we can so code that we can make up a field force without actually physically applying to it, we don't need a master. Then we can put all this inside the space suit, and be much better off, and also use it in other environments and get a superior feedback. I don't know whether that is feasible.

CHAIRMAN JOHNSEN: We have people here who are working the EMG control, and they are going to talk later on. I will ask them to answer this at that time.

MR. GOERTZ: Just a short comment. It may be possible to do away with the master, but I feel strongly that great improvements in master-slaves can be made while still using the normal human hand to operate the master arm. In fact, it seems to me that the full dexterity of the hand can one day be extended to the remote locations.

COMMENT: What we are talking about here are two competitive ways of attaining this sophistication. The winning approach is to provide an improved sense of control, position, and force in the ways we are talking about, with special forces, transducers, and better servo techniques. Myoelectric signalling some day will be a very sophisticated way of doing things. But if we are going to advance this art, should we hold back by waiting for EMG? I think we can go faster by working with the sensor technique and using an exoskeleton master.

QUESTION: Do you have any brief comments about improved depth perception?

MR. GOERTZ: Depth perception can be improved if the slave TV has all five degrees of freedom. Then, when the operator moves his head from side to side he gets depth information to some extent. Stereo is really needed but none has been developed, that I know about, that is very good. We tried some years ago and others have tried. Unless the

two pictures are high quality and very well lined up, it doesn't work well. Better quality TV may be a prerequisite to good stereo.

COMMENT: I agree. We tried it and found it was useless — that is, stereo TV as compared to a crisp resolution of a single system. There are many ways of seeing depth. The psychologists tell us there are eleven distinct functions in the eye to give you depth perception.

CHAIRMAN JOHNSEN: I have rearranged the program once more because, again, we have a gentleman who has some other appointments to keep. Lee Harrison, who is now President of Control Image Corporation here in Denver, has done some work using a television display, if you want to call it that, requiring minimum bandwidth.

MR. LEE HARRISON: I say hello to all of you that I remember from some of these other conferences. First I want to show you a slide of our software for programming a computer which is specially built to make images. The programming input is quite low bandwidth, to create motion; I have some moving pictures of anthropomorphic forms that we have photographed in real time off a cathode-ray tube. This is Debbie, who was on the TV program called "Turn On" that got turned off, if you remember (fig. 34). Debbie is a dancer. She came out from Hollywood to supply some motion to our anthropometric harness, which was made of tinker toys and potentiometers at the joints, and rubber bands and a few things like that. That's Debbie, a little out of focus, but this was taken off of another picture. We were picking up some joint motion, and she had a lot of motions we couldn't pick up, but it was an interesting start.

Now, I will show you some of the things she actually programmed. What we lacked was the hardware for making a coordinate transform between Debbie and the computer. We are using normal X Y Z coordinates of the computer so that when we run the film, you'll see some of the things we have done.

The idea which is applicable to teleoperation is that we take the high bandwidth, a priori information (that which you already know about the basic image format), and contain this inside the computer. We animate the image or make it move with very low bandwidth inputs. We sample what a few potentiometers on a body are doing, or on a remote manipula-

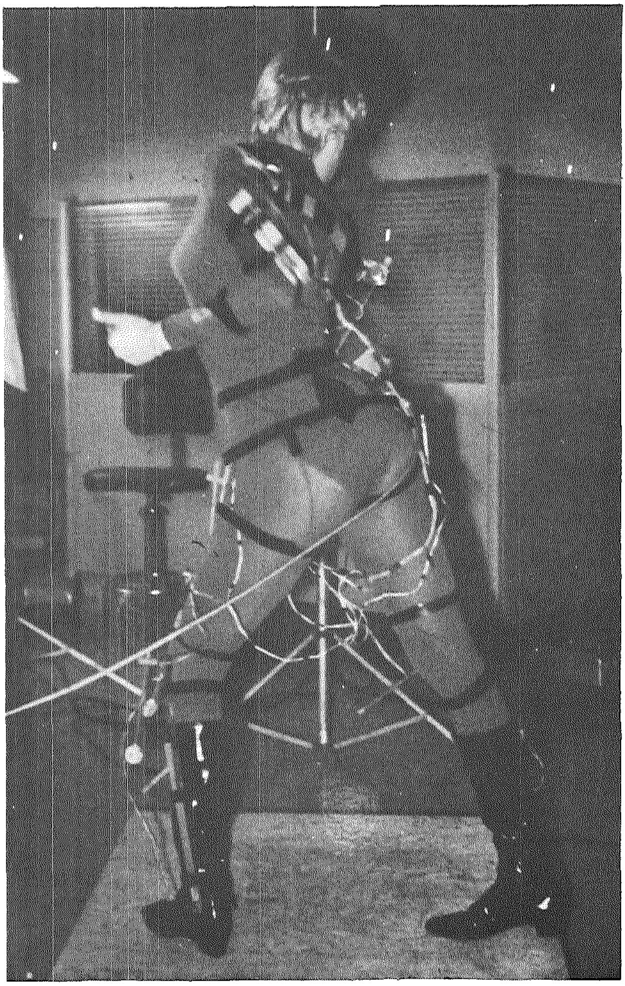


FIGURE 34.

tor, and this information makes the image conform to the model. The feedback is visual. So the coordinate transforms on something as complicated as a human body have to be fairly accurate. Anyway, here is the movie.

I think the application to teleoperation should be very clear. If, for example, you want to concentrate your bandwidth on the actual target of the task that you are performing but at the same time with low bandwidth orient yourself on a wide screen with manipulator status and position, this can be done. You know what manipulators look like; that means you have the a priori information which visually defines the manipulators to any degree you want at the receiver. Combining animation produced by computer with a standard TV picture oriented properly in the display space can give the operator a better view of the task at reduced bandwidth. Murky viewing conditions would not affect the view of the manipulator.

Any questions?

QUESTION: What was the bandwidth on the Debbie demonstration?

MR. HARRISON: We sampled Debbie 48 times a second for each degree of freedom that we could measure. But it was 2 or 3 hundred cycles, I suppose. I haven't figured it out lately. Debbie could use up 1500 cycles with no problem.

COMMENT: It appeared to me her eyes were closing as well in reconstruction.

MR. HARRISON: That was probably just programmed in; some of the sound that was in the music, or somebody would hit the microphone. We weren't particularly trying to animate the mouth of the dancer.

MR. FLATAU: It seems to me the human eye does precisely what you described, has a high resolution...and a much lower resolution. If we knew how to develop with the... resolution of the human eye in the dynamic range, we would probably need a multibandwidth of cycles; I don't know quite what it is, but something fairly wide. I would like to hear your comment about the possibility of superimposing depth perception—in other words, several things to do with computer plotting of a three-dimensional figure, something like that. Have you done that?

MR. HARRISON: We have the capability. The equations inside the computer (it is primarily an analog computer which solves three simultaneous equations) define the motions of a point as it moves about in space, focusing on the object that you have programmed. All you need is another monitor, or another eye channel if you will, to produce 3-D effects. The equations are producing their movements for any view in three-dimensional space, and you happen to take one view of that, but you can simultaneously take another view that represents the distance between your eyes.

CHAIRMAN JOHNSEN: May I interrupt a minute? Mr. Harrison is going to show some more movies tonight. I think some of his other movies are going to generate further questions because he has a way of fleshing out what he calls bones, which might be of interest to a number of you people. So why don't we defer any further questions until tonight. Our next topic will be Head Control Television, and John Chatten will discuss the system he has been working on for quite a while.

MR. JOHN CHATTEN, Control Data Corporation: I am reporting on a program which has been under way at Control Data for about two-and-a-half years under Defense Department sponsorship. Its objective is the development of a novel type of a head-aimed television system. A head-aimed television system is designed from the outset for use by a single operator and is intended to provide him with as complete a sense of visual presence at a remote site as possible. It consists of three basics or subsystems, the first a remotely located camera, which is gimbal-mounted and controllable in at least two degrees of rotational freedom. Second, the distinctive thing about head-aimed television systems is the fact that the display device is coupled to the operator's head in such a manner that, regardless of how he moves his head, the display surface always remains centered about the axis of his head and presents a picture to his central vision. Third, associated with the head-coupled display device is a head-position sensor which generates control signals pointing the camera in such a way that it mimics the motion of the operator's head.

The history of head-aimed television goes back about twelve or thirteen years. Systems previously built had as a display a single miniature cathode-ray tube mounted on the operator's head, either helmet-mounted or goggle-mounted, and a head-position sensor which controlled a single gimbal-mounted TV camera. These systems have adequately demon-

strated the effectiveness of head control in camera aiming. I think most people who have tried these systems have soon been satisfied with that aspect of it. The major problem with television, which some of the speakers have touched on, is the obvious inferiority of its image compared with direct visual presence. This results in the limited number of revolvable elements available with realizable television images. This problem manifests itself in two ways, making the operator feel deprived of both resolving power and field of view. The designer has a choice in setting up a system providing a broad field of view with poor resolving power, or good resolving power with a small field of view. We addressed ourselves to this particular problem on the project being reported here.

Figure 35 shows the distribution of resolving power of human vision in the horizontal plane. It shows that exceptional resolving power exists in a very narrow area about the central part of the field. At this point it is roughly one minute of arc. Within a few degrees it drops off to a tenth that value.

With a single field television system you have your choice of supplying data perhaps as shown by one of the two dotted curves. The bottom block corresponds to a viewing system with inferior resolving power displayed over a 68-degree field of view. The other dotted block corresponds to a presentation that supplies detail nearly matching the acuity of human vision. To accomplish this it is necessary to restrict the field of view to 8 degrees. Either dotted block represents a television system having 1000 scanning lines and requiring a 20-MHz video bandwidth. We try to approximate the resolving capability of the eye with a composite image made of two images such as those shown dotted in figure 35 — a foveal image having high resolution and a narrow field of view and a peripheral image having low resolution but a broad field of view. The experimental remote viewing system which has been built using this concept is properly termed "head-aimed television with a foveal/peripheral image format" or "foveal-HAT" for short.

When utilizing foveal-HAT, the operator's field of view is circular and subtends 68 degrees with respect to his eye. The resolving power across this field of view is uniform at approximately 11 minutes of arc except for the central 8 degrees of the field, where the resolving power improves to approximately 1.5 minutes. As the operator moves his head,

this composite image always remains centered in the overall field of view. He gets the impression he is wearing goggles which restrict his vision to a 68-degree field of view, the central part of the goggles being made of much clearer glass than the rest.

Figure 36 shows the first assembled camera. It demonstrates clearly how the camera system works. There are two stationary vidicon cameras in this implementation. They are put on a common optic axis through the use of a beam-spliting mirror, and they view off a front surface mirror which is gimbal-mounted and remotely controlled in azimuth and elevation.

Figure 37 shows a newer camera which has a little more structural integrity than the first one. It has been designed for use on a vehicle. In this case, the two vidicon cameras are looking straight up through an aperture in the azimuth-bearing of the mirror gimbal. An additional feature of this second camera is the capability of remotely zooming the lens that generates the foveal image.

Figures 38 and 39 show the viewing device. On this project we made the decision to concentrate on optimizing optical quality, and the best solution with this design objective in mind is to couple a television image from high-quality stationary displays to the operator's field of view through a jointed optical relay. Figure 38 is the relay and the head-piece part of the system. This is hung from a small tray anchored to a wall. The upper portion of the viewing device is stationary and consists of two lenses which take the images from two individual monitors and combine them optically into a composite one-inch image having the foveal/peripheral image format. The remainder of the linkage is movable and so articulated that the operator can turn his head with the three rotational degrees of freedom. Inside the tubes are lenses and mirrors which simply relay the one-inch diameter imput image to an eyepiece. The eyepiece is mounted in a headpiece which, in this case, is a formed plastic mask fitted in a frame having a headband. The eyepiece takes the one-inch image and displays it to the operator as subtending 68 degrees. The main weight of the device is supported by the tray and the joints are either spring-loaded or so located that he doesn't feel the weight of any portion of the device. When he takes the device off it will just float in space in

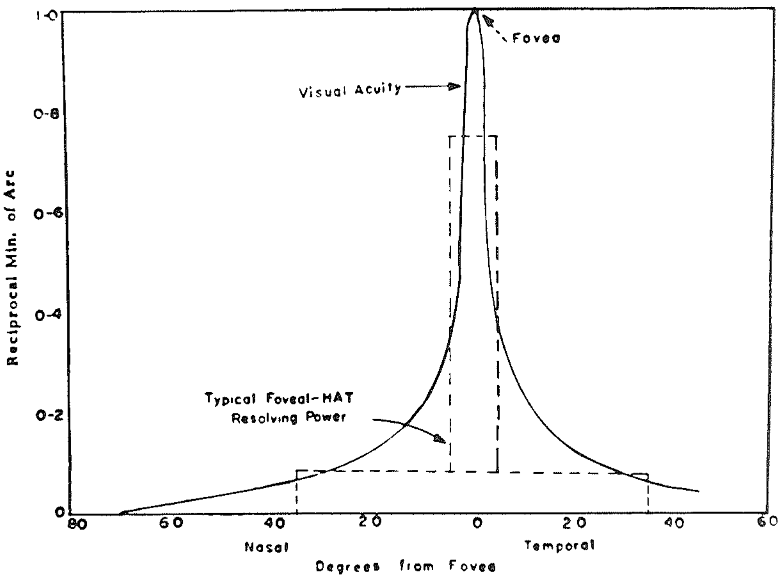


FIGURE 35.

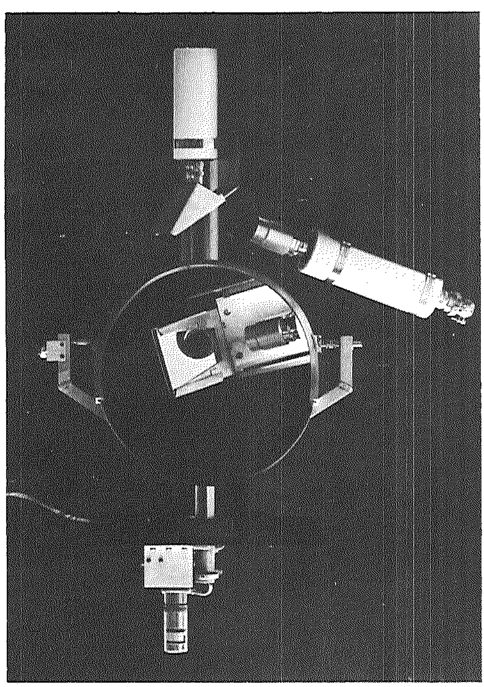


FIGURE 36.

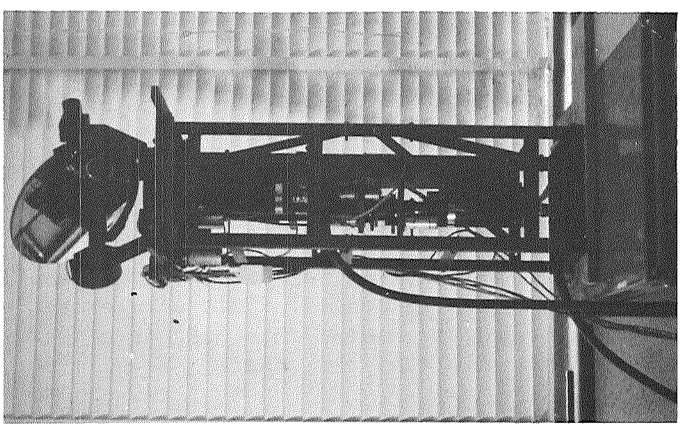


FIGURE 37.

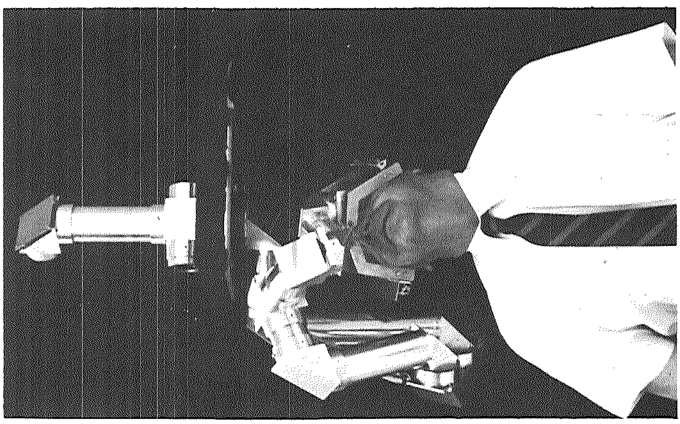


FIGURE 38.

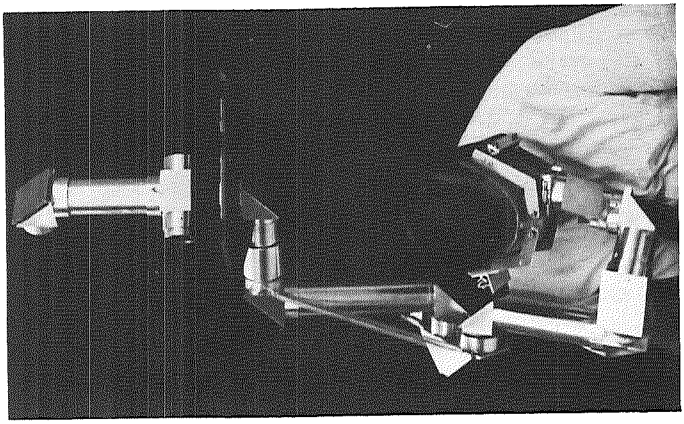


FIGURE 39.

front of his face. The only time he senses the mass is when he is accelerating and is aware of the initial load. The weight of the movable portion of the display is about eight pounds. The head-position sensor is, of course, elementary with this kind of a display device since it is just a matter of sensing the deflection of the joints of the viewing device.

The experimental foveal-HAT system was completed about one year ago. Since that time we have been performing a program of experimental evaluation. The evaluation tests are generally a matter of establishing standard tasks to be performed using foveal-HAT and one or more alternative remote viewing systems, the most successful alternative being a joy stick-aimed camera with remotely controlled zoom capability. These tests and results obtained to date are too preliminary to report on here. However, several statements can be made:

1. In all tests, foveal-HAT has enabled equivalent or superior performance to alternate systems tested.

2. In pure tracking tasks involving rapid target motion over wide angles, head control resulted in a markedly superior performance over joy stick control of the camera.

3. For tasks demanding high resolving power in the remote visual field approaching one minute of arc, it is far more effective to give the operator some optical magnification rather than trying to supply important data to him at or near the resolving power of his eye. It is these results that led us to incorporate the zoom fovea in the new camera implementation.

Currently we are in the process of installing the foveal-HAT camera on a drone vehicle. In this case, it is a Ford pickup truck converted to drone control to determine how well we can perform various driving tasks utilizing the foveal head-aimed TV system as against other techniques such as fixed camera and manually controlled single field cameras.

CHAIRMAN JOHNSEN: Question?

MR. HAWKINS: Mr. Chatten, do you think it necessary in these experiments that the central field of view register with the outside view, or would it be just as effective to have one magnified more than the others?

MR. CHATTEN: It is a matter of degree. Precise registry is not important. The operator very quickly learns not to get anything important in the scene right at that dividing line. When you introduce magnification in the foveal field with no other change in system parameters, tracking ability will be degraded because of the mismatch between head and camera motion. The advantage of this system, when tracking moving objects or performing surveillance from a moving vehicle, is the fact that there is unity optical magnification and unity mechanical magnification in the system; so when you move your head the scene moves in exactly the way your brain expects it to move and you maintain your sense of orientation.

QUESTION: What commercial or industrial applications have you postulated for this?

MR. CHATTEN: My personal feeling is that the most significant application for this kind of a system, with the full capability of the wide field of view and the higher resolving power fovea, is remote control of vehicles where the objective is to achieve a fairly high degree of performance in challenging terrain. However, there are many other possible applications and, of course, the television control of remote manipulators is one of them. There was some discussion earlier, when Mr. Goertz was describing his experience, of the procedures when the manipulator hand is separated by more than the angular field of view of the television system and the object you want to grasp. You have to first find the manipulator, then track it to the object. The broad peripheral field would be of enormous help in this respect, I would imagine.

QUESTION: Does it seem to offer any use in underseas operation?

MR. CHATTEN: I am not familiar with the requirements of the underseas work. I see no reason why it should not.

DR. JAMES BLISS: Is there any advantage in being able to record eye movements within the head and then using a smaller field of view perhaps, but then instead of keeping the high resolution field ... being able to position it around the field as the eye moves?

MR. CHATTEN: Yes, that would improve performance very significantly if it could be done effectively. The engineering of such a system is pretty challenging.

MR. FLATAU: I think you mentioned the bandwidth requirement, but I didn't get it. Would you state it again?

MR. CHATTEN: The bandwidth requirement depends on the resolving powers that you are aiming for. The figures I was quoting of 700 resolvable elements across either the foveal or peripheral images correspond to two 20-megacycle channels.

MR. GOERTZ: I would just like to ask this question. Have you tried the head-viewing thing, and how would you compare it to a stationary device — the little tubes?

MR. CHATTEN: One of the major problems with systems with little tubes is the tubes themselves. It is a substantial engineering effort to get high resolving power and brightness on those tubes, and I would say every system I have seen that utilizes miniature helmet-mounted cathode-ray tubes is limited in resolving power by the display tubes themselves. In a conventional television system, however, one that uses a large 17- or 21-inch monitor, the display itself only slightly affects the total resolving power of the system. In that case it is usually the data link or the camera that limits the resolving power.

MR. FLATAU: How much force does it take to move that optical relay?

MR. CHATTEN: I haven't measured it. It is moved by the head, of course.

MR. FLATAU: Does it move easily?

MR. CHATTEN: Depends on how rapidly you want to accelerate or decelerate, and on how well the individual fits the headpiece. I find personally I can move it with no difficulty and over long periods of time with steps of, say, from 90 degrees in a half a second — this sort of thing.

CHAIRMAN JOHNSEN: I would like to point out one thing which hasn't been mentioned, which I think is very impressive, and that is that one of the tests of this thing is to be able to read fine print on a moving object.

QUESTION: Does the system provide for any head translation just for comfort — that does not impart an indexing or a tracking command?

MR. CHATTEN: No, there are only three degrees of freedom of the head — primarily rotational. I don't quite know how to define this in terms of pure head translation and rotation, but there is translation associated with some of the degrees of freedom. If you were to look at the center of gravity of the head, it translates with some of the motions.

QUESTION: So each of these motions would impart a tracking command?

MR. CHATTEN: Yes. The location of the three axes of rotation were chosen to be those most comfortable for the operator. They do not cross in the center of the head, so some head translation accompanies rotation. However, only rotation is sensed.

At this point Dr. Charles B. Magee took over as Chairman.

CHAIRMAN MAGEE: I believe we are ready to start. The next speaker will be Dr. Thomas B. Sheridan from M.I.T.

DR. SHERIDAN: Our activity at M.I.T. is academic. Our labor force consists of graduate students. We are developing no hardware, but are working on theory and concepts, laboratory experiments, and I think in the long run trying to develop a theory for manipulation that goes beyond servomechanism. What is now called old-fashioned control theory as compared with optimal or modern control theory is not really adequate to describe what manipulation is, because manipulation is a many-dimensional process. It is a process that stops and starts; it is not to be characterized by continuous dynamics.

Several years ago, starting with a thesis by William R. Ferrell, formerly one of my students and now a colleague in the Mechanical Engineering Department at M.I.T., we became convinced that anybody who thought he was going to operate a teleoperator system continuously when the time delay is longer than about a tenth of a second (i.e., longer than what corresponds to synchronous satellite distance) was kidding himself. The reason is that you simply can't do continuous control through a pure time delay, not if you have loop gain greater than one at frequencies greater than those for which a half cycle is the time delay.

We demonstrated this in the laboratory. Russ Ferrell came up with a prediction, followed by experimental verification which indicated that the time it takes to complete a task was equal to the time it takes to do the job with no time delay, plus a number N times a quantity including time delay and reaction time. That gives you a plot of the completion time for the task as a function of the delay. Something that looks like a signal-to-noise ratio, which corresponds to number N of correction, moves to achieve the required position tolerance.

The number N has to do with the number of stops and waits for feedback in doing a task. In other words, if you commit yourself open loop to a certain part of the task, at some point you simply wait because you are afraid to go on for fear you'll drop something or push something where you don't mean it to be pushed. The number N can be worked out in the laboratory; Mr. Ferrell did this for simple tasks; in fact, he predicted it. Recently on a consulting venture for GE, as part of their Air Force project, we verified his model in six degrees of freedom with an ANF manipulator hooked to a computer.

One of the things that we're doing now is putting, in addition to a pure time delay in the loop, a visco-inertial time lag. Dynamically, these are clearly two different animals. The time lag tends to reduce the time delay. Clearly, if you have a long inertial lag in a system and a very short time delay, you're never going to see the time delay. Then of course, your system is still slow. So the move and wait strategy that Ferrell uncovered becomes a little sloppier, but it's still there, and it becomes somewhat random as to how long the operator waits.

About this point in time we convinced ourselves that the only right way to do this job is to use a computer in the loop, where the man talks to a computer over long distance telemetry, and the computer, which is local to the manipulator, takes care of the control. I am going to refer to a slide depicting the supervised computer-manipulator system (fig. 40). We have had in the laboratory for several years now a fairly simple setup consisting of a modified AMF or Model 8 manipulator equipped with stepping motors, which are driven by a small computer (PDP-8) augmented with some other equipment. We do experiments on how to give commands: typing into a teletypewriter or moving joy sticks or other

controls. We also experiment with the strategy by which the computer effects local control between times the man interacts.

I had a discussion with Mr. Allen — I guess he has left — I was going to disagree with him. My point of view concerned the time delay problem. I am convinced that nobody is going to be very happy doing manipulation, except very crude manipulation, with a time delay in a continuous loop at lunar distances. The human factors problems that we really need to study, call them control problems if you will, are problems of (a) how do you talk to a computer about manipulation, and (b) how do you organize the computer to do little pieces of the tasks by itself.

In talking to a computer about manipulation, we have been using two modes of control. One is analogic, and the other is symbolic. My contention is that you want to use both of these kinds of control in talking to a computer about manipulation or in giving it instructions. It's much as you would instruct a small child to move a toy. You would point (analogic) and would also use words (symbolic). Analogic commands are those we use in pushing, pulling, pointing, doing things in the real words that are in some sense an analog or have a physical dimension or direction analogous to what we want done. We built an arm that in some ways was similar to that shown by our German visitor in his slide this morning. It was not a positional device, but merely an on-off directional one with seven degrees of freedom. Its operator only has on-off switches in all seven degrees of freedom, but it is also anthropomorphic with the arm. We found that we could position-control our Model-8 manipulator quite nicely with this. You didn't have to think about which switches you were throwing; you simply went ahead and did it, just kept orienting your arm more or less in the direction of the manipulator.

Symbolic commands are related series of alpha-numeric symbols, letters, and numbers like you use on a typewriter or like the astronaut uses when he directs the guidance system in Apollo. In the context of this manipulation simulation I referred to, one of our students has written a compiler he calls Man-Tran for manipulation translate. It allows the operator to type statements that are like English sentences when the arguments are such things as which degree of freedom to move, how far to go, what the stopping conditions are, and so on. There are more or less three levels of

instructions in this Man-Tran language. There are the direct imperative commands: "Move a certain degree of freedom at a certain distance." There are contingency commands of the type: "Do such-and-such, but if a certain thing happens, like if your touch sensor touches something (we have on our manipulator here some crude touch sensors), then stop." Or "If you touch something on the outside, go into another subroutine." In addition to the simple imperatives of "Do a certain thing," "Go to a certain place," or "Move a certain degree of freedom," there are the contingency commands which essentially are a listing of conditions: if this, do this; if that, do that; if something unexpected, do something else.

There are prenamed configurations. For example, if the manipulator is in a certain configuration, and you know you later will want to come back to that configuration, you say, "I'm there, I'm going to name it Alpha," and the computer is going to remember what Alpha is. Sometime later when I want to come back to Alpha, I'll just say "Do Alpha," and the computer will know to look up on a list. Assuming it knows where it is and knows where Alpha was, it can go right back to Alpha by the best path. Finally, there is a kind of hierarchical structure where a prearrangement of certain statements in turn call other statements. Man-Tran has all these features in it and they work. We are now struggling at higher level problems where you say "Pick up the block" or "Put the nut on the bolt" or something like this, and the program has to have the sense to call these kinds of subroutines in the right order. So this is still very much of an ongoing type of activity.

Now, there is one other area I wanted to mention, and I am going to drag you into just a little bit of abstract conceptualization. The problem here is that of how you structurally represent a manipulation task. Once you can formally structure what the task is for a computer, there are many ways it can work things out for itself, but it is imperative that you have this formal structure. Otherwise, the computer doesn't have any idea what you are talking about. You have to represent the whole manipulation task in registers of the computer's memory.

The control engineers have something called "state space," and what state space is, really, is just a formal representation of all the permissible states the system of interest can take and how these are related. If we are

sending a rocket to the moon, these states might be all the combinations of position, velocity, and acceleration. You've got to "discretize" this for a computer, so you've got a three-dimensional array of states for the rocket problem.

A couple of years ago, one of our students by the name Dan Whitney, also a colleague on the faculty at M.I.T., did a thesis where he showed how manipulation tasks could be represented formally in a state space. The notion is that instead of these states being simply the positions, velocities, accelerations, and higher derivatives, if you wish, of one object, they include the whole configuration of objects. Assume, for example, that in figure 41 you have to simplify it to a 20 x 20 space, a very coarse grid. You've got a manipulator M, consisting of two jaws which open to one of 5 states. You want to move over to pick up a block A, and once you've got block A picked up—let's say it is a tool of some kind—you want to go down and do something to part B. After you have done something in part B, you want to bring the manipulator back to the lower left of the position space. You could formally represent the state of the situation in any one point in time by one of 20 x 20 places where the manipulator could be times 5 for jaw opening (allowing no rotations), one of 20 x 20 places where part A could be, and one of 20 x 20 where part B could be. So, you've got a $20^2 \times 20^2 \times 20^2$, which is 6.4×10^7, a very big number of possible states.

Now, if one could get away with this crazy business and represent it in a computer, then all you would need is an algorithm for finding a least-cost path through this state space. That's what optimal control is about. You represent the states, and you have a way of evaluating the costs to go from one state to another; then you put some kind of analytical or numerical method to work to find out the least-cost path. This is ridiculous, because representing all combinations of many objects in a big space like this is too big a number for most computers to handle. What really excites me these days — I am working up to the point where I think we need human factors studies — is a way to figure out how a man could not only communicate to a computer in semi-natural language about what he wants done, but also how he can make the job easier for the computer by simplifying the state space.

Suppose I just cut this big square into little squares so these are little 10 x 10 quarters. Assume in quarter one

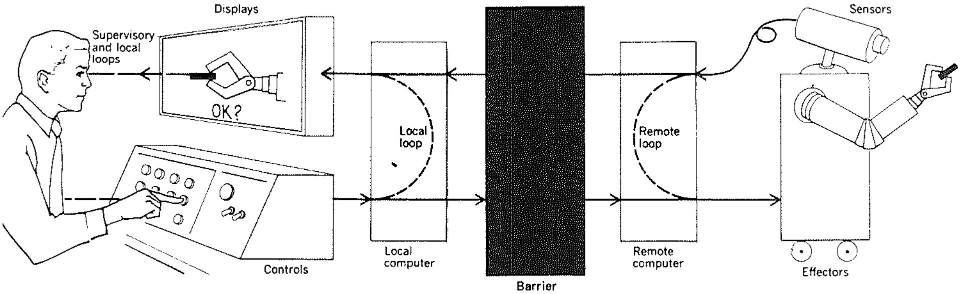


FIGURE 40.

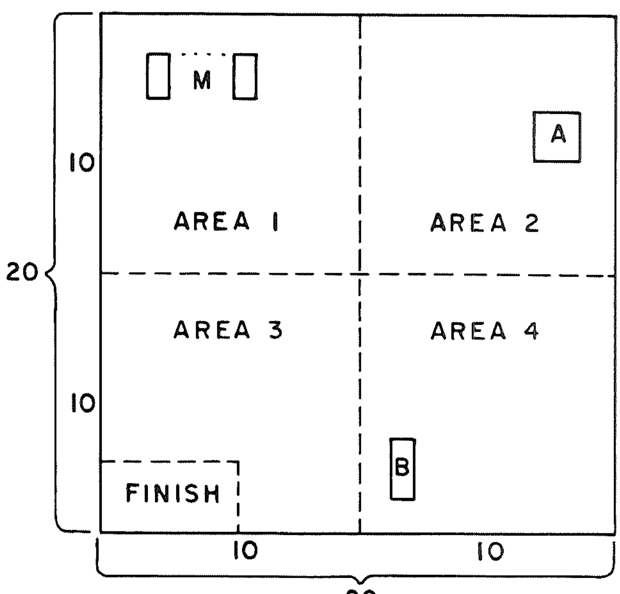


FIGURE 41.

all I need to do is move into quarter two so I have only 10 states for the manipulator to pass through to be in area 2 for sure. In area 2, I am only concerned with the manipulator's jaws and with object A. Here, I've got 10^2 for the manipulator to be anywhere in the area, and it is going to be one of 5 states of being open. Also, I've 10^2 states for object A in area 2. Now, if I've got object A in the jaws and I want to move down to 3 and do something to object B, I have really only got 2 separate objects. So I've got 100 states for B within area 3. Finally, assume I just want to move the jaws back to some starting position in area 4, I then have 10 x 5 for area 4. Adding up the separate state spaces, all I've really got to be concerned with is something like 6×10^4 different states, and I can now turn the job over to my computer, according to some algorithm for minimizing cost within subspaces. I've also cut down my tasks by an order of almost 10^4 by simply imposing cutting and ordering constraints. That's the kind of things humans are really good at, but computers are really hopeless. Communicating this kind of insight to a remote manipulator computer is where I think the real progress is to be made.

Let me conclude by mentioning one very exciting application we haven't talked much about. This is in the area of telediagnosis in medical problems. We have begun to work with a Dr. Bird at Massachusetts General Hospital who has set up a telediagnostic clinic. There is microwave TV from Massachusetts General Hospital to Logan Airport where a clinic is manned by a nurse. Doctors at the hospital are now diagnosing patients at the airport over this TV linkage. We are excited about this because we can see that by adding manipulators you can adjust lights, you can stick a TV camera or a fiber bundle into the mouth and the ears, and you can place stethoscopes to all kinds of things. We have begun doing some of this and it looks pretty good so far.

If I'm not over my time, let me mention one other project that Jim Bliss and I were talking about, which is another kind of pet area. Sometime ago we were experimenting with tactile displays, an area in which Mr. Bliss has since done much work. One of the things we did was to develop a very simple system which we actually put on this same manipulator, consisting of a curved or deformable plastic mirror with a light grid on it. On the surface of the manipulator jaw was the transparent elastic material, the surface side of which had a mirror facing inside (there was an abrasion-resistant material on the very outer surface). If you picked up an object in

the jaws, the mirror curved in a shape to conform to the object. If you bounced light (from inside the jaw finger) off the mirror and through an optical grid pattern, you saw through a coherent fiber bundle a distorted grid pattern which corresponded to the stresses imposed by this object. Then you look at this with a TV camera and you essentially see what you are touching. We have tried to interest some of the manipulator users in this and have been unsuccessful. I guess the reason is because people don't think in terms of seeing a tactile pattern. This is not seeing the object itself; but the force pattern. If anybody thinks they can use this, I'd be glad to give it to them.

CHAIRMAN MAGEE: Any questions or comments?

MR. ALLEN: I would like to comment here that when I was talking about time delay, I meant the delay throughout the entire system. One of the big things that hasn't been studied, and you just touched on it in the work you did with GE, was the time delay on the force feedback. This is an unknown area, extremely important. Again, if you get the force feedback on things like fitting fairly large nuts or putting connectors together and you get your alignment visually, the delay really doesn't mean very much because you feel it. Even with manipulators you have a clunk. So that was what I was talking about in the fairly crude systems where we are just replacing boxes, changing connectors, and such. The only part of the human factor that wasn't clear to us was the effect of the time delay on the force feedback.

DR. SHERIDAN: I didn't mean to attack you, as you know. I am quite in sympathy with 99.9 percent of what you said earlier. Russ Ferrell also did, and I am sorry he isn't here to give us a very nice little study on force feedback with time delay. This was done with a simple two-dimensional manipulator in which he showed that the problem is really more complicated with time delay in the force feedback load. In the visual loop you can go ahead open loop, with your eyes closed as it were, and sit there and wait for feedback. In the force feedback case you can't because if you display the force back to the same hand that is putting the input into the system, you'll unavoidably put the disturbance back in. You get a kick; that kick will automatically force you to put another input into the system, and so on. Mr. Ferrell felt that the way to work with time delay in a force feedback system is to turn it on just when you want to make a critical

measurement—when you want to look for the bump, as it were—and as soon as you find where the bump is, turn it off again. It is a delicate reaching out. As soon as you touch, you turn it off, because if you keep it there you're going to be in trouble.

MR. HAMILTON, Institute for Defense Analyses: I would think that your device for seeing what you are feeling would be helpful to medical doctors in examining patients for cancer.

DR. SHERIDAN: It is too crude for that at this stage of development. The reason we quit working on it was because we ran into problems of mirrorizing flexible plastics — getting a more flexible plastic, with a good mirror surface.

CHAIRMAN MAGEE: Thank you. We have another visitor from Europe. This will be Mr. Vertut from the French Atomic Energy Commission.

MR. VERTUT: I shall give a short report on the activity of teleoperators in Europe. The first time I came here in '62 I had the pleasure of having Ralph Mosher describe the powered manipulator, 600-pound handling capacity, which had been designed in this period for meeting the problems of dismantling fuel elements. Six or seven units of these manipulators have been built and they meet some of the requirements we were talking of yesterday, in particular the rigidity making possible a good position control. They should be programmed easily and will equip the dismantling cells of the French power breeder Phenix. Then we worked on master-slaves, and maybe we designed one of the first completely articulated master-slaves, without any telescopic motion. It is curious to see that this disposition is always used for servomanipulators but was not used till now in mechanical master-slaves.

This manipulator has been, for me, an opportunity of opening close relations with Central Research. As you know, Central Research is manufacturing this arm as Model H, with two symmetrical upper arms and parallel lower arms. Now we have a project using parts of this standard mechanical arm to make a servo. We are working on tests of the servo link. I'm in a rather big discussion with Carl Flatau about the concept of using cable transmissions between the servo drive and terminal device, or servo installed in the arm. I should

try to make the servo model using the maximum part of the standard arm and installing the major part of the servo drives in a balancing part, the whole arm pivoting around the shoulder. However, the major work we have done this past two years is in the field of vehicles.

Figure 42 shows a British concept, a remote inspection vehicle (RIVET) due to H.S. Ballinger. It shows how the disposition can be quite a good replacement of the man in different positions. This machine is still at the stage of the mockups to show the possibility of crossing very bad obstacles as shown on figure 43. This is a three-degree-of-freedom vehicle, instead of two like the usual vehicles with two tracks. So I should like to compare that vehicle with the next one now in development in my group (fig. 44). It is a vehicle having to perform work remotely around the laboratories for survey after nuclear accidents. The problem is quite different from that of the vehicle to be carried inside a laboratory on good ground. In this type of vehicle we know the MRMU which is radio controlled. The attempt here was to make self-powered vehicles to carry the future servomanipulators. To test the lowest need for power we decided not to use the track but wheels instead.

This vehicle was shown in the Atom Fair in Washington in November 1968. The concept is based on identical wheel units comprising the motorized steering motion. Such wheels can be installed in any disposition. This vehicle is square shaped, the wheel being protected behind. The body electronics will be located in the central space, and the batteries between the wheels. (At the show in Washington where the picture on figure 44 was taken, the batteries were in the central space and the electronics on a flat disposition over the vehicle.)

Figure 45 shows one wheel unit, total height 50 cm. The upper part comprises slip rings for power and a steering position potentiometer. The vertical cylindrical part contains the gear motor for steering. The propulsion gear motor is in the center of the wheel. The tire is a standard small plane tire; pressure is 1/3 kg/cm^2. The special feature of this vehicle is its ability to converge the axes of the different wheels from driving straight as well in one direction or in the perpendicular one (in X or Y direction) up to rotating around its own center. These might be explained by figure 46. This is a geometrical explanation

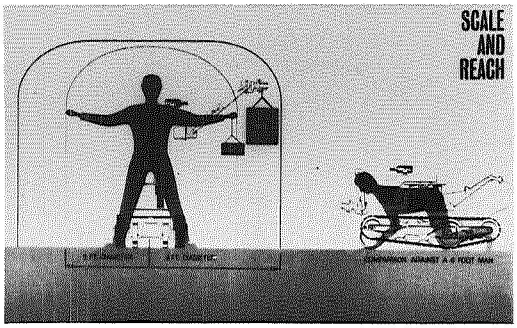


FIGURE 42.

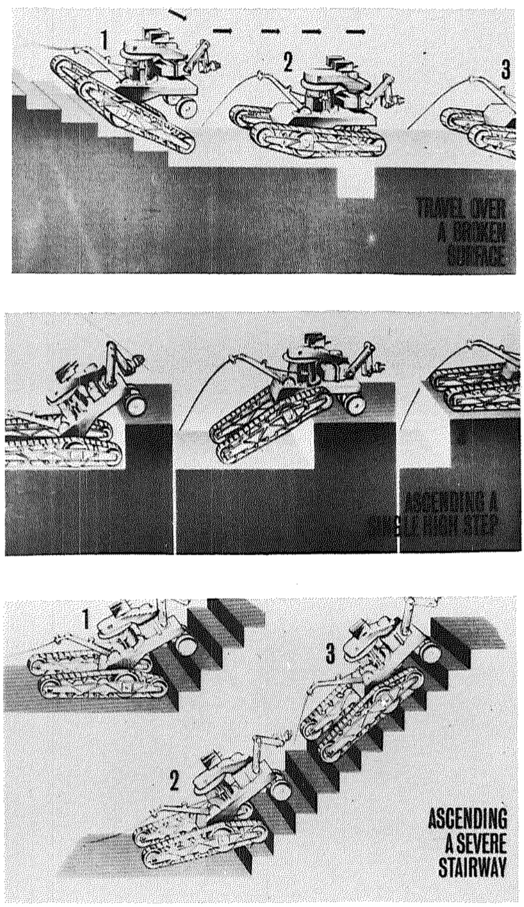


FIGURE 43.

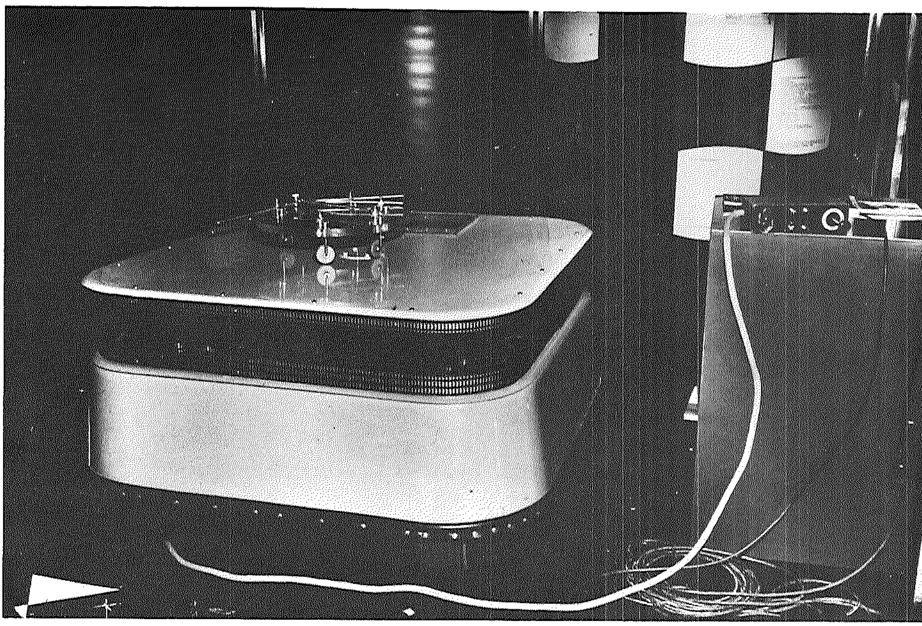


FIGURE 44.

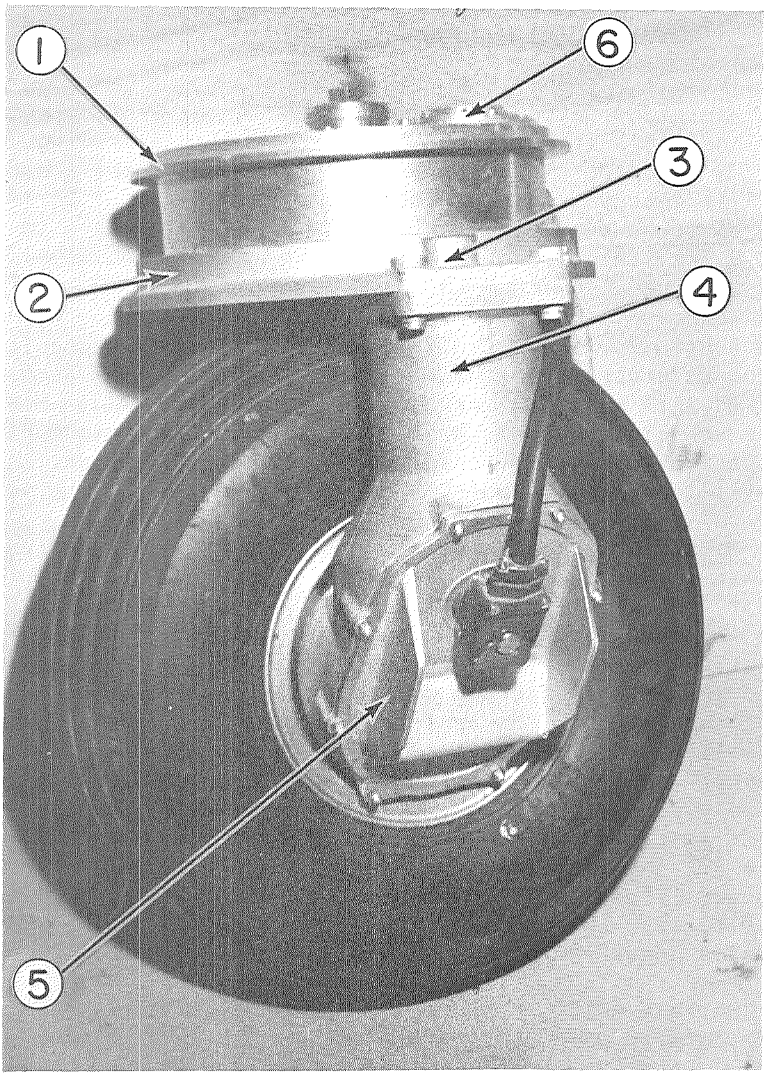


FIGURE 45.

of how the wheels of the vehicle can be converged. They are located on the circle in figure 46.. If we look to one of the wheels, we can easily mechanically converge the axes of the wheel, to a point 0 inside the diameter AB of the vehicle.

This needs quite short levers, but if we want to put the wheel parallel, it becomes impossible. Using a driving lever OW, and the axis of the wheel WO' symmetrical around WB, 0' is the conjugated point of 0 to the circle. So if we still converge driving levers of the different wheels to point 0 into the circle and drive the wheels with reverse angles, we converge them to the conjugated point 0'. By this means we have the simple system shown in figure 47. We have two potentiometers and two levers. We move them mechanically and the reference from these potentiometers is just used and reversed into position servos to drive the different wheels of the vehicle. When we arrive at a position of the center of rotation on A or B, we switch the servo to a direct angle and still converge to point 0' up to the center of the vehicle. When we want to come from X-axis to the Y-axis, we have to permutate different wheels symmetrically around a diagonal. If we want to make a rectangular vehicle, it would be similar, of course. We would have three potentiometers because when you want to come from the X-direction to the Y, it is not symmetrical around the diagonals. Another device in the mechanical steering computer controls relative speeds of the wheels. An important advantage of speed servo drives s on wheels is to be able to cross very bad obstacles as 0.8 radius of the wheels. Another advantage is the ability to move on very smooth ground. Now, with this vehicle the project is to install two servomanipulators as shown in figure 48. Manipulators should be on telescopic rotating columns. TV and positioning arms should be moving in the same time with the shoulder pivot. The vehicle itself will be tested under radio control with TV by next fall.

CHAIRMAN MAGEE: Thank you. Questions? Comments? Thank you very much.

Our next speaker will be Dr. Michael J. Wargo of Dunlap and Associates, Inc. (ref. 1).

DR. WARGO: About three years ago, Dunlap and Associates, Inc., was awarded a contract by NASA's Electronics Research Center to investigate the limitations on human operator response speed, frequency, and flexibility in the manual

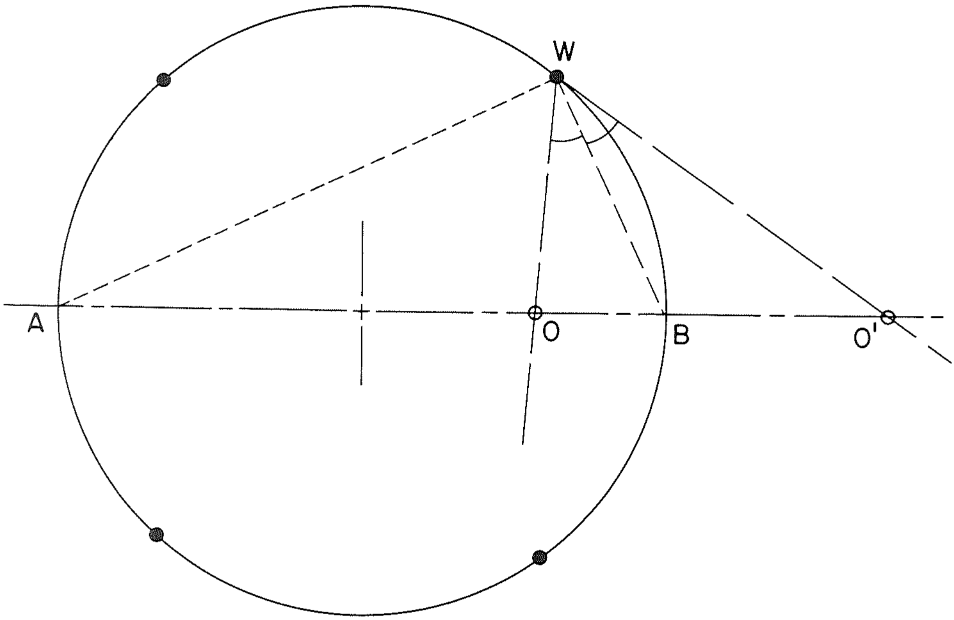


FIGURE 46.

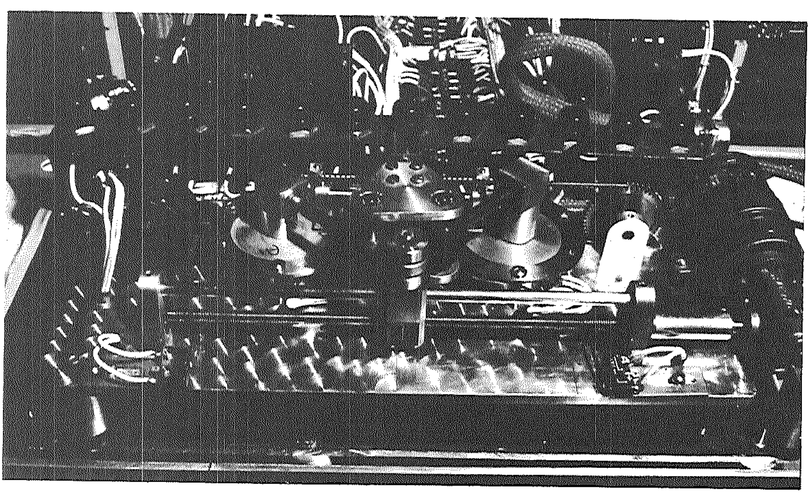


FIGURE 47.

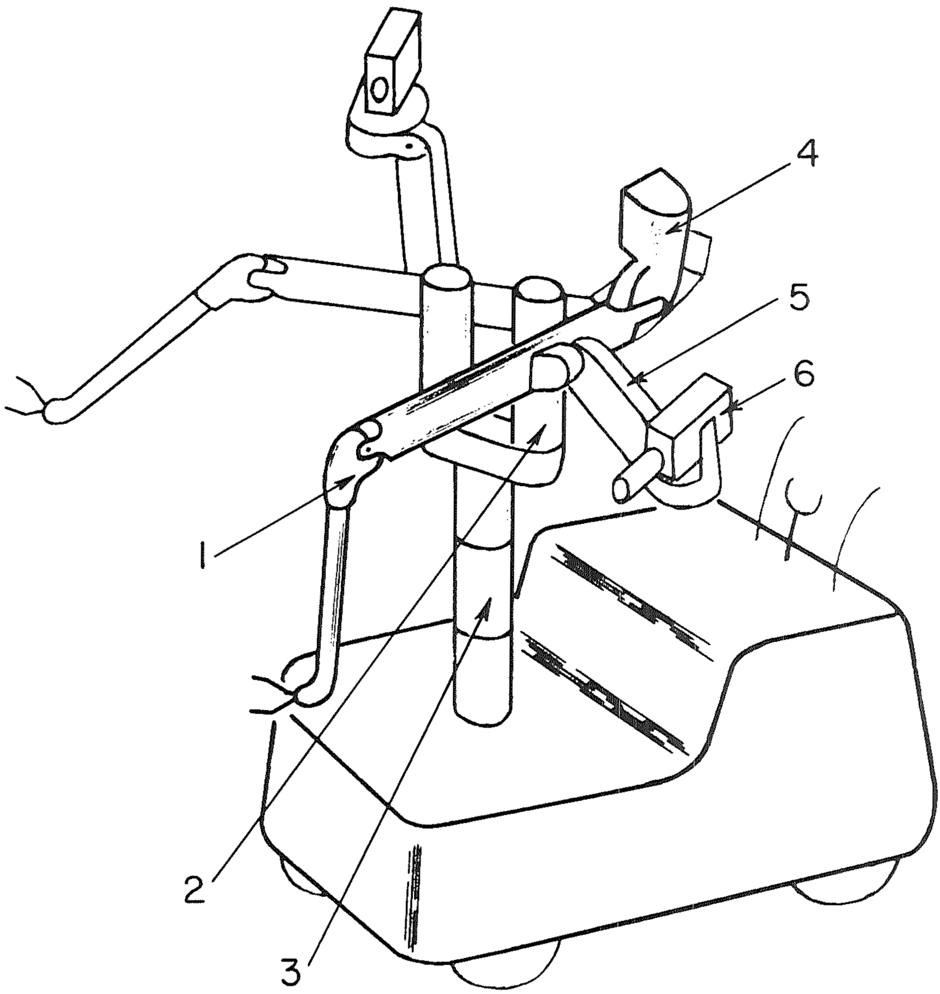


FIGURE 48.

control context (ref. 2). The goals of the project were: (a) to define and analyze the limitations imposed by man on system response speed, frequency, and flexibility, (b) to develop techniques for overcoming those limitations, and (c) to demonstrate the application of the developed techniques in the manual control context. Our work on this project was completed in September of 1967. The project final report details the results of our work. Today I will briefly summarize that work since it has direct relevance to the development of advanced teleoperator systems.

Figure 49 schematically represents the various sources of delays and lags that can occur in a closed loop manual control system. In such manual control systems response speed and response bandwidth are limited by system- and operator-imposed lags and delays (ref. 3). System lags and delays are defined as those that can be attributed to the system's design characteristics and/or to the environment in which the system must operate. They include transmission delays and control, and display lags and delays. Operator lags and delays are defined as those inherent in the structure of the operating organisms. They include man's input acquisition and receptor delays, afferent and efferent neural transmission delays, central process (i.e., mental) delays, muscle activation lags, and movement time. Delays and lags, whether operator or system imposed, tend to limit the response speed (reaction time) and response frequency (response bandwidth) of manual control systems.

The focus of our research was operator-imposed lags and delays. A review and analysis of the neurophysiological literature relating to human response speed resulted in the following estimates for the fastest simple and choice reaction times by a human operator:

DELAY BASIS	DELAY IN MILLISECONDS	
	SIMPLE	CHOICE
Receptor delays	1-38	1-38
Afferent transmission delays	2-100	2-100
Central process delays	7-100	90-300
Efferent transmission delays	10-20	10-20
Muscle latency and activation time	30-70	30-70
Reaction time or total delay	113-328	133-528

Receptor delays are defined as those attributable to the transduction process occurring at the sensory receptor level. Each sense modality has its own unique receptor delay. The ear, for example, is about fifteen times faster than the eye in terms of receptor delay. Neural transmission delays are those due to the conduction velocity of the various fibers that make up the neural pathways. Central process delays are those that result from an organism's perceptual and cognitive processes. Central delays, both perceptual and cognitive, are in general the longest and most variable of the human operator's delays. Muscle latency, the latent period between myoneural-junction depolarization and the beginning of a muscle response is, in man, in the order of a few milliseconds. Activation time, the interval between the beginning of depolarization and the peak of muscle tension, however, requires something in the order of 30 to 70 milliseconds.

The above estimates assume that the stimulus-subject interface is optimum, and the subject is well practiced and prewarned a few seconds prior to stimulus presentation. The total delays estimated above correspond to those figures cited in the psychological literature for simple and two-to-four-choice reaction times. On the basis of a review and analysis of the psychological literature relating to the stimulus-receptor, central process and response member aspects of human response time, the most promising techniques for increasing man's response speed and frequency, appear to be:

1. The use of sense modalities with short receptor delays (a saving up to approximately 30 msec).

2. Cross-modality input display (an additional saving of up to 20 msec).

3. Facilitation of operator input-output prediction (theoretically, if there is perfect prediction the operator overcomes his reaction time delay).

4. The use of responding members closer to the cortex (a saving of up to 30 msec).

5. The use of responding members with optimum force-inertia ratios (a saving up to 90 msec).

6. The direct use of muscle action potentials for control (theoretically a saving of up to 100 msec).

It should be noted that none of the above suggest bypassing the operator's central process delays. To do so would be tantamount to eliminating the operator himself from the control system since the primary reason for including him is to take advantage of his perceptual and cognitive flexibility. Nevertheless, on the basis of the above estimates it is theoretically possible to reduce human reaction time in the order of 20 to 200 msec (ref. 4).

In terms of human response flexibility (i.e., the ability to simultaneously control several inputs) man is limited by the dearth of research directed at taking advantage of responding members other than those of the hands, arms, and feet. A review of the research relating to prosthetic and orthotic device development, however, led to the following suggestions for increasing human response flexibility:

1. Training the human operator to use some of his more exotic output members (e.g., the ear).

2. The direct use of output members (other than the limbs) over which the operator has relatively precise voluntary control (e.g., facial muscles and the eye).

3. The use of operator muscle action potentials as a source of control signals.

On the basis of the above and a review of the literature relating to advanced control and display devices, it was concluded that the most practical means for improving human operator response speed, frequency, and flexibility in the manual control context was to use auditory or simultaneous cross-modality and display systems in combination with a muscle action potential (MAP) control device. It was anticipated that a manual control device incorporating these techniques would substantially increase human operator response speed, frequency, and flexibility. However, prior to the development of such a device, it was decided to further evaluate those techniques in a situation more analogous to manual control than the simple reaction time situation. A disjunctive (choice) reaction time situation, configured so that it resembled a one-axis compensatory tracking task, was selected as the vehicle for evaluation. Evaluation consisted of a comparison of MAP and hand-switch disjunctive reaction times to visual, auditory, and combined visual-auditory displays (ref. 5).

The hand-switch and MAP reaction times of three adult male subjects were compared. The visual display used in the study consisted of a two-inch horizontal line centered on the face of a cathode ray-oscilloscope (CRO). The line was pseudorandomly programmed to deflect approximately three inches above or below the center position of the scope. The subject's task was to return the line to center position as quickly as possible via a compensatory microswitch deflection or a flick of the wrist in the case of MAP control. The auditory display consisted of a binaurally presented 880-Hz tone which corresponded to the center line on the visual display. The tone, presented via a headset, was forced to jump from 880 Hz to 400 Hz by the same forcing-function program used with the visual display system. The subject's task was to return the deflected tone as quickly as possible to 880 Hz via a compensatory movement of the microswitch or a flick of the wrist in the case of MAP control. The spring-centered microswitch was positioned at arm level and below the center of the visual display. The control-display configuration required a downward deflection of the microswitch to lower the line or tone and vice versa. A very small force and slight deflection of the switch was sufficient to return the display to its center position or frequency. MAP signals were picked up from the subject's right forearm by a BIOCOM Model 121 differential amplifier. The two responses required for centering the display were flicks of the wrists in opposite directions.

Three adult males were pretrained until they reached a plateau in terms of a stabilized mean reaction time. Fifty warm-up trials were given to each subject prior to data collection at each display-control combination. Figure 50 illustrates the mean reaction times pooled for the three subjects. Each subject emitted two hundred responses at each control-display combination. As figure 50 illustrates, (a) MAP responses were consistently and significantly faster than hand-switch responses across display modalities and (b) the display effects were mixed within the switch response mode. However, within the MAP mode of response the combination display was faster than the auditory display and it, in turn, was faster than the visual display. Analysis of variance and comparisons of means verified the statistical significance of the results (ref. 5). The results of this preliminary study encouraged the project team to develop a muscle-action-potential control device with both an auditory and visual display. The design and construction of the device is detailed in our final report. My primary concern today is to detail the results of the device demonstration.

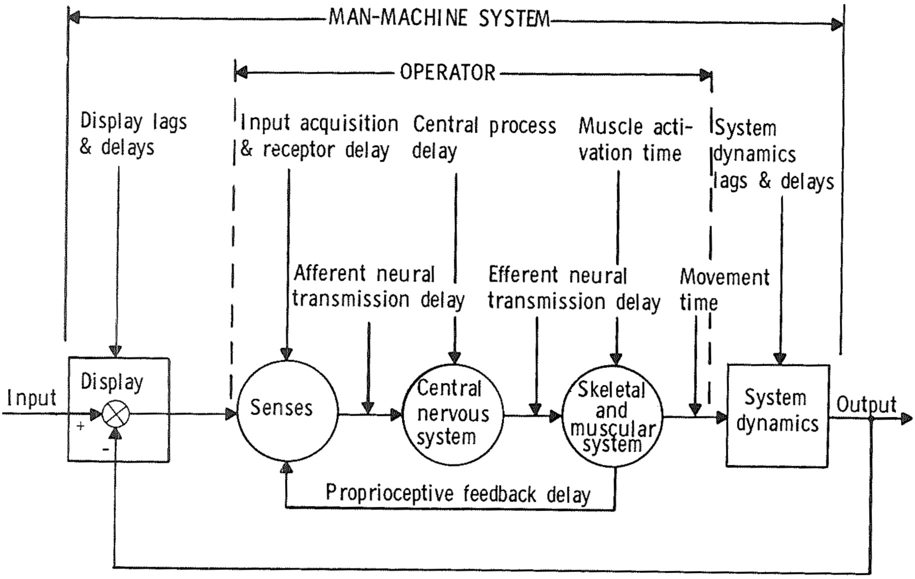


FIGURE 49.

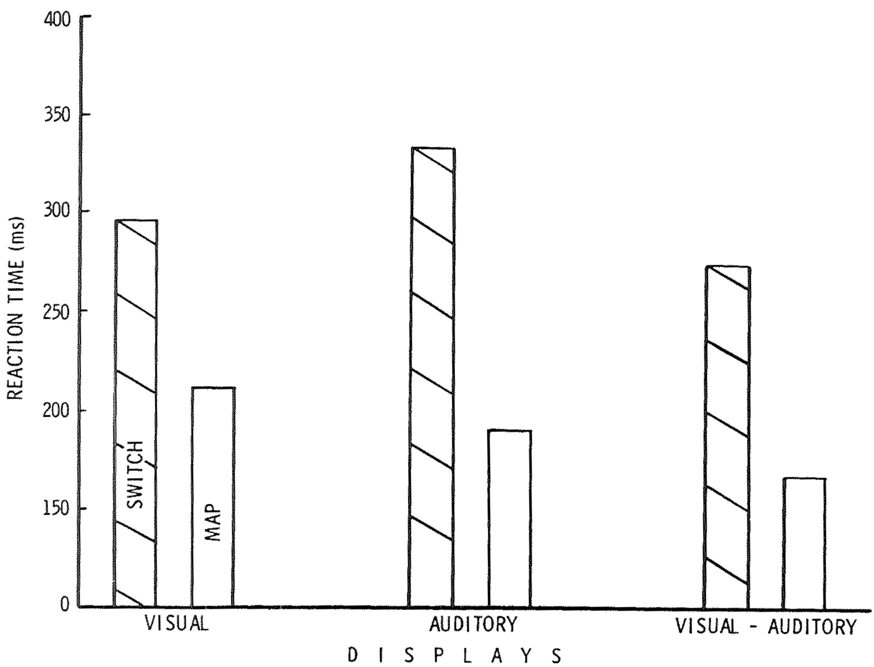


FIGURE 50.

The demonstration device can be best described as a self-contained, two-axis MAP control system with three display modes: visual, auditory, and combined visual-auditory display. Control signals for the device can be detected from most muscle groups on the human body. The control output of the device is three state — positive, zero, or negative.

The primary goal of the demonstration was to show that the reduction in reaction time due to MAP control translates into an increased response bandwidth for the human operator. In addition to demonstrating the increase in human operator response frequency that accrues from MAP control, a secondary goal of the study was to demonstrate the increased flexibility of response made possible via MAP control from muscle groups other than those of the limbs. The demonstration consisted of a comparison of two conventional hand controls with MAP control from the cheek muscles of the subject. The tracking system employed was based on acceleration control. The display used in the demonstration was the device's visual compensatory display. The subject was required to null the error in a one-axis tracking situation using the visual display and each of the three controls. The two conventional controls consisted of a bang-bang displacement and a bang-bang isometric joy stick. MAP control signals were picked up from the subject's cheek muscles. Figure 51 illustrates the mask developed to hold the electrodes on the subject's face. The tracking system employed was an adaptive forcing-function frequency system. The five sine waves comprising the forcing function were automatically speeded up or slowed down in unison to keep the operator tracking at a preselected error criterion. When the operator's error was greater than criterion, the forcing-function frequency decreased; when error was less than criterion, the forcing function frequency increased. In that way the operator error was kept constant and the dependent variable became the forcing-function frequency (expressed as percent of its maximum) that the operator could control within the fixed criterion of error. The independent variables of the study were forcing-function amplitude and control type. The experimental design consisted of a comparison of the three controllers in terms of maximum forcing function controllable across a range of forcing-function amplitudes.

The forcing function consisted of the sum of 5 sine waves of equal amplitude, proportionately spaced in the decade between 0.025 and 0.25 Hz at maximum value. The adaptive circuit automatically adjusted the "percent of maxi-

mum" forcing-function frequency displayed to the operator. Thus at 50 percent score, forcing-function frequency would range from 0.0125 to 0.135 Hz. The amplitude of the forcing function was adjustable to a maximum of 100 percent of the display scale; e.g., if the forcing-function amplitude was set at 90 percent, the maximum it could displace the displayed error signal was 90 percent of the scale. The error criterion was set at 10 percent of the display scale. Whenever error exceeded 10 percent, the forcing function decreased in frequency and vice versa.

One adult male was employed as the subject for the preliminary demonstration. The subject was familiar with the adaptive feature of the tracking system and had considerable experience in acceleration tracking both with displacement and isometric control. His experience with MAP control via the cheek muscles was limited, totaling perhaps one hour of sporadic tracking. The experimental design required the subject to track for 3 minutes with each controller at forcing-function frequency amplitudes of 60, 70, 80, 90, and 100 percent of maximum amplitude. In all, fifteen 3-minute tracking runs were required to complete the design. During the short rest period after each 3-minute run the subject received performance feedback. Shortly after completion of all the runs the design was replicated. The order of runs was systematically varied to balance out learning and fatigue effects.

Figure 52 depicts the results obtained on the second run through the design. This figure indicates that (a) as the maximum amplitude of the forcing function increased, the maximum controllable forcing-function frequency decreased for all three controllers and (b) MAP control via the cheek muscles was consistently superior to either displacement or isometric control. On the basis of these results it appears that a significant increase in human-operator response frequency and flexibility can accrue from the use of MAP control.

The results of this research program indicate that MAP control can be used to significantly increase human-operator response speed (reaction time), response bandwidth (frequency of response), and response flexibility (via use of muscle groups other than those of the limbs) in the manual control context. Consequently, in the design of teleoperator systems it is necessary for the system designer to consider MAP control when system response speed, bandwidth, or human-operator response flexibility are important design considerations.

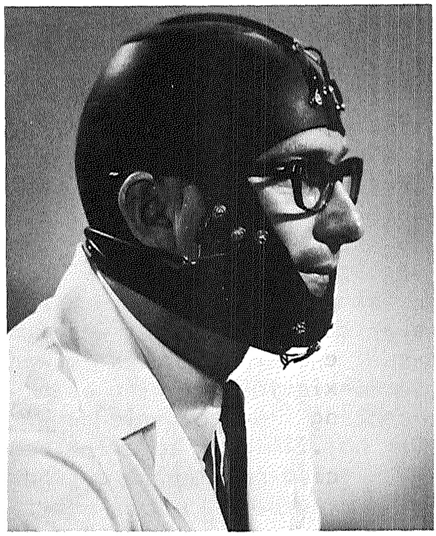


FIGURE 51.

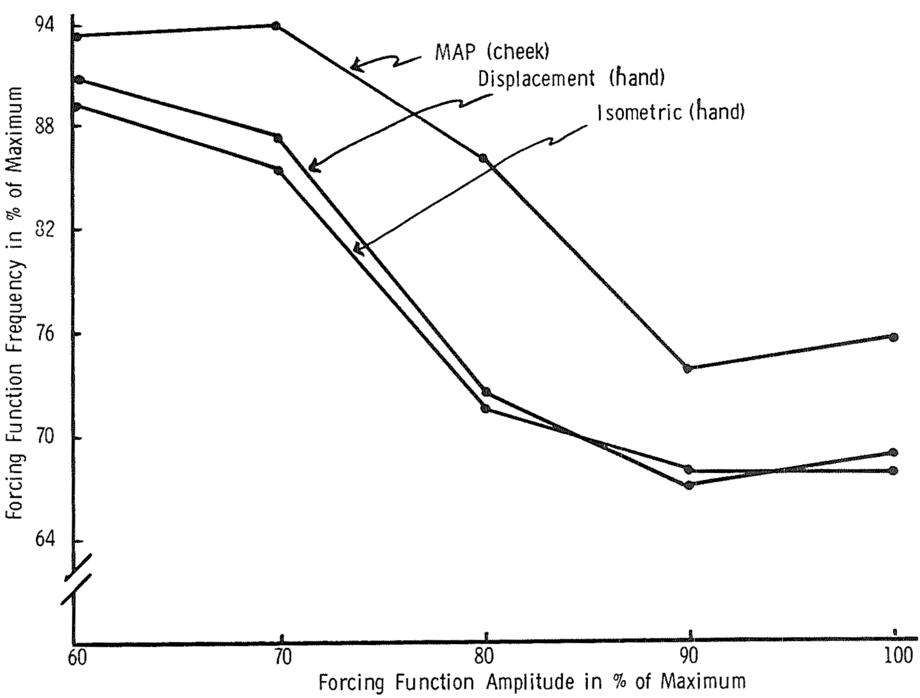


FIGURE 52.

MR. FLATAU: Do you remember what the frequency was at the end of the graph in figure 52?

MR. WARGO: The adaptive circuit in the device demonstration study adjusted the forcing-function frequency in terms of percent of maximum. Since this function consisted of five inharmonic sine waves of equal amplitude proportionately spaced in the decade between 0.025 and 0.25 Hz, the maximum forcing-function frequency at any point in figure 52 can be determined by selecting the percentage point of interest and taking that percentage of the forcing-function frequency range. For example, in figure 52, with the displacement control the subject was capable of controlling approximately 90 percent of the maximum forcing-function frequency at 60 percent of the maximum forcing-function amplitude. He was therefore controlling frequencies over 90 percent of the range, or from .0225 to .225 Hz /.90(.025) = .0225 and .90 (.25) = .225/, at a forcing function amplitude of 60 percent of the display scale.

We are currently interested in further development of MAP control devices and in more extensive research relating to human response limitations on system response, speed, frequency, and flexibility. However, our funds have run out and we are having some difficulty in interesting NASA or other funding agencies in further work in the area.

REFERENCES (Dr. Michael J. Wargo)

1. Currently at Fairview State Hospital, Costa Mesa, California.

2. The work here described was supported by NASA Electronic Research Center under Contract NAS 12-103, Dr. Charles R. Kelly, Principal Investigator. See: Wargo, M.J.; Kelley, C.R.; Mitchell, M.B.; and Prosen, D.J.: Human Operator Response Speed, Frequency, and Flexibility — A Review Analysis and Device Demonstration. Washington, D.C., NASA CR-874, 1967.

3. The Laplace transfer function for a delay is e-ps, and for first and second order lags is 1/1 + Ts and 1/(1 + TS) (1 + Ts) respectively, where e is the base of the natural logarithm system, T is the delay or lag in seconds, and s is the Laplace operator.

4. Wargo, M.J.: Human Operator Response Speed, Frequency, and Flexibility — A Review and Analysis. Human Factors, 1967, 9, (3), pp. 221-238.

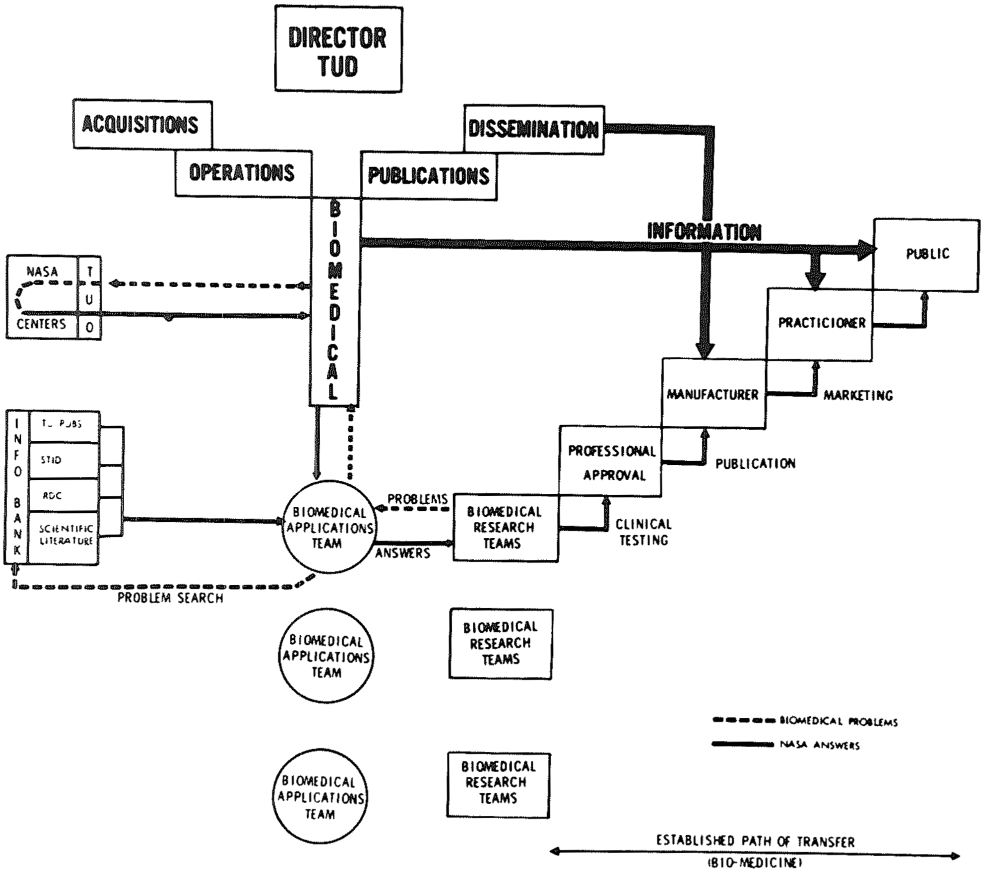
5. Wargo, M.J.; Kelley, C.R.; Prosen, D.J.; and Mitchell, M.B.: Muscle Action Potential and Hand-Switch Disjunctive Reaction Time to Visual, Auditory, and Combined Visual-Auditory Displays. IEEE Transactions on Human Factors in Electronics, 1967, 8, (3), pp. 223-236.

CHAIRMAN MAGEE: Any questions or comments? Thank you.

Our next speaker will be Dr. Quentin L. Hartwig from George Washington University.

DR. HARTWIG: Thank you, Dr. Magee. I am a physiologist with the George Washington School of Medicine, and am involved in an experiment that is conducted by the Office of Technology Utilization of NASA to accelerate the flow of aerospace technology to the needs of medicine. This slide (fig. 53) gives you an idea of an experimental approach to interacting sources and aerospace solutions with biomedical problems. The letters TUD stand for Technology Utilization Division. This is the source of funding for the program. On the left side there are sources of aerospace technology: NASA Research Centers and NASA grantees and contractors. They provide aerospace solutions. There is also an aerospace information bank which includes Scientific and Technical Aerospace Reports (STAR), and International Aerospace Abstracts (IAA). Most of the information being generated in the space program finds its way into this bank as technical publications and these can be searched for by computer.

So far we have talked about solutions. On the right side of the chart is the source of problems, medicine. The first question that had to be asked was: what is the flow of information in medicine? Where do ideas start, and if these ideas have application in the practice of medicine, how do they eventually diffuse from the researcher to the practitioner and therefore the public — you and me? It was decided that the source with the time, talent, and facilities to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PROBLEMS
ANSWERS
BIOMEDICAL RESEARCH TEAMS
CLINICAL TESTING
PROBLEM SEARCH
BIOMEDICAL APPLICATIONS TEAM
BIOMEDICAL RESEARCH TEAMS
BIOMEDICAL APPLICATIONS TEAM
BIOMEDICAL RESEARCH TEAMS
BIOMEDICAL PROBLEMS
NASA ANSWERS
ESTABLISHED PATH OF TRANSFER
(BIO-MEDICINE)

FIGURE 53.

evaluate aerospace technology was the medical researcher. If the technology had validity, it would travel the traditional information path in medicine and be utilized in medical services.

To bring the medical researcher new technology, three biomedical application teams were established. Teams were established because if one looked at past applications of aerospace technology, it was noted that there were personal kinds of interface between solutions and problems. The interdisciplinary team is organized to go into medical schools and specify problems in interdisciplinary language. The language can be used to search the entire data bank. Solutions to medical problems have no disciplinary boundaries. They can come from engineering, physics, chemistry, and math as well as space biology and medicine. The biomedical application teams work with researchers in 15 medical schools and research institutes in a wide range of fields. This program has been successful in relating aerospace technology to medical problems. In fact, of the three transfers that Dr. Welles spoke of yesterday, the teams were directly responsible for two and had an involvement in the third.

We at George Washington School of Medicine assist NASA in the management of the three teams, and the interaction between the medical researchers and the sources of information. In this position, we have the opportunity to view the whole information process in medicine. We can step back and get an idea of where the barriers are to applications of new knowledge in medicine. This has a practical advantage because, as Dr. Brown mentioned this morning, you hear a great deal. For example, you are reminded of the electronic arms that have been around for 15 or 20 years, yet this technology for one reason or another has yet to reach the practitioner for application to the public.

What are the problems in applying technology to medicine? Well,one major problem is what I call the "facility gap." When I speak of the facility gap I am talking about a comparison of the facilities which generate information in the whole world to facilities available to the medical profession in applying technical information. The latter capability is minuscule. When you go into the medical setting and you say, "What is your capability of applying new technology? How many engineers do you have? What kind of facilities do you have to design and fabricate equipment?" The answer is virtually nothing. So in the world today there

is a tremendous facility capability of generating knowledge, but little capability of applying it. The medical community must generate this capability. Then there is the problem with successful prototype equipment and devices. Prototypes are often jerry-built on a small workbench by one or two engineers doing everything from conceptualizing and drafting to fabricating. This ingenuity has led to a pile-up of prototypes because manufacturers are reluctant to put in the reengineering money that will turn the prototype into the commercial product. They are reluctant because it very often requires significant resources to transform the prototype into something that has market appeal and reliability. The major factor in his decision is anticipated sales volume. Often, the volume is simply not adequate. As a result, one hears about the prototypes but seldom sees the commercial product. This has caused a strained relationship between the physician and patient. The patient as a taxpayer hears about an electronic arm and wants to be fitted with one. The patient's hopes turn to frustration when his doctor must tell him that despite the many prototype arms that have been developed, commercial versions have not met adequate performance standards to replace mechnical prostheses. One can't blame the manufacturers, because, after all, they must make a profit and they have their stockholders to answer to. Thank you.

CHAIRMAN MAGEE: Questions or comments?

MR. WIRTA: I have a question regarding the introduction of these thoughts to the biomedical research teams. There are a lot of problems I'd like to solve if I had the information, but I could spend more than twice my time searching and sifting from the information and find only a small share that would be useful. Do you have in mind some kind of techniques which would make the transfer of information much more efficient than it is at the present time?

DR. HARTWIG: Unfortunately, science in the past has been concerned with the publication rather than the diffusion of results. Despite millions of scientific articles there are still tremendous social problems. In part, the act of sifting through volumes of literature is being assisted by computerized information banks. So a user can tie into a computer source of information like Dr. Welles mentioned, such as the regional dissemination centers that NASA supports. Industry can buy into a center and have search conducted for them. Some of the abstracting organizations like Chemical Abstracts provide some computer searching. So this

is one way in which you can reduce the amount of time that it takes to search for solutions.

MR. SCHWARTZ, Denver Research Institute: On some of these services we have tried to use — computer services — one of the things seems to be key words you use. They are very general. You end up with a tremendous amount of information coming back, of which one-tenth or so is really applicable. We have tried this on things such as the eye.

DR. HARTWIG: With an RDC, for example?

MR. SCHWARTZ: In NASA we actually gave them a literature search — key words. It was a good effort, I would say, but actually what it paid off in was something else. If you look through the key words, they are too broad to really do what I think you are attempting to do. I think this is something that has to be done but right now the key words are much too general.

DR. HARTWIG: You really have to interact with the fellow who designs research strategy. It is extremely important that he fully understands your problems and objectives. This will allow him to devise the most relevant search strategy.

DR. MOE, University of Denver: This particular search was directly with NASA back East, not with the Regional Dissemination Center. I talked to them on the phone. There was no interaction after the first request.

DR. HARTWIG: You talked to the fellow who made the strategy?

DR. MOE: Yes, but it was a fairly brief conversation.

DR. HARTWIG: It is certainly one thing that we encourage the biomedical applications teams to do. All of their searches are conducted by an RDC. One just has to get into close communication with the individual who develops the search strategy so that he can eliminate as much of the chaff as possible. However, you run into another situation. We deal with some investigators who don't want you to do that. They say, "I want a broad type of search." He may want to see things I would never have thought of as relevant but which may spark an idea in his mind.

MR. SCHWARTZ: This would be a channel of key words it seems to me. To put it another way, right now there is a very broad level.

DR. HARTWIG: In structuring a search strategy, you can use the terms <u>and</u>, <u>or</u>, and <u>not</u>. This allows the flexibility of gate setting.

DR. MOE: I think a bigger problem really is the data base that you are working from. We have had different searches made from different data bases. If you are just beginning in a new area, these searches can be very useful. If you have been working it it for a while and know a lot and are looking for more, you become unhappy with a search, no matter who you get it from. The data base simply is not big enough to get much more information.

DR. HARTWIG: Well, very often you have to just expand the sources of information. It would be nice if there was one data base in the United States that covered everything, where you go to one source. That just isn't available. But there is a document about an inch thick, titled "Information Resources in the United States." In it are listed a large number of organizations that will answer specialized questions, very often for nothing.

CHAIRMAN MAGEE: There is a question over here.

DR. FARR: I just had a comment. One of the inadequacies of the data search lies with the scientist authoring the paper. The Defense Documentation Center (DDC) has a mandatory form which goes into all Department of Defense (DOD) reports. This calls for a descriptive listing by the authors. It is still optional, however, and the DDC people have to put it in themselves. But the author has the opportunity to list all the descriptive or key terms that he wishes to. If this was done consistently and carefully, in great detail, you would find searches a thousand times easier and more profitable. Then, of course, you need a computer program which can correlate between general and specific terms so that it knocks down or eliminates by cross-checking many of these things which are inapplicable to your needs. This will take care of your biocompatibility even if you don't use the terms.

You also need very educated people doing the searches, because if you can provide them a paragraph of what it is you are looking for, they can then convert that into terms with

which they are familiar in their system. This is, unfortunately, hard to get because these people are poorly paid and any good people go on into scientific research or administration.

DR. HARTWIG: There is far more effort in generating knowledge, really, than there is in its application.

DR. SCHWARTZ: There is a problem here, too, in the communications between the life sciences and physical sciences; at any rate, sometimes. Your key words could come out differently, depending on who writes the article. If someone from the opposite science is looking, he may be in trouble. This is an area that probably causes some problems.

DR. HARTWIG: Well, I think the language gap tends to dissolve when the facility gap is decreased, and also if instrumentation can be made available.

DR. FARR: One more point. Those of you who are associated with technical journals might see what you can do to have every journal article contain a list of key terms at the end or the beginning of the article. This is the first start towards getting the author's own descriptive terms into that article, and journals do not usually do this.

CHAIRMAN MAGEE: Any other comments? Thank you.

There are no more names on the formal program. Is there anyone else who has something they would like to contribute? I would be very reluctant to make any attempt at all to summarize these proceedings. As I said yesterday morning, our job at the University is to disseminate information; that I think we have done.

Thank you all very much for coming, and for your contributions to this colloquium. The conference is adjourned.

LIST OF ATTENDEES

Mr. James R. Allen
Project Director
Rancho Los Amigos Hospital
12826 Hawthorn Street
Downey, CA 90242

Mr. William H. Allen
Mission Analysis Division
Ames Research Center—NASA
Moffett Field, CA 94035
Present Address:
NASA Headquarters Code RMC
Washington, D.C. 20546

Dr. James C. Bliss
Bioinformation Systems Group
K-1054
Stanford Research Institute
Menlo Park, CA 94025

Col. Paul W. Brown, MC
Office of the Chief
Orthopedic Service
Fitzsimons General Hospital
Denver, CO 80240

Mr. John B. Chatten
Control Data Corporation
1062 Lancaster Pike
Rosemont, PA 19010

Dr. Frank G. Chesley
Central Research Laboratory
Red Wing, MN 55066

Mr. Arthur J. Critchlow
Mobility Systems, Inc.
3530 De La Cruz Blvd.
Santa Clara, CA 95050

Dr. Stanley Deutsch, Chief
Systems Research & Analysis
NASA
Washington, D.C. 20546

Mr. Norman F. Diedrich
Case Western Reserve University
Case Institute of Technology
10900 Euclid Avenue
Cleveland, OH 44106

Dr. B.L. Dorman
Vice President
Procurement and Material
Aerojet-General Corporation
9100 East Flair Drive
El Monte, CA 91731

Mr. Laurence T. Eck
Technical Specialist
SNPO-Nevada Extension
P.O. Box 1
Jackass Flats, NV 89023

Dr. Marshall J. Farr
Assistant Director
Engineering Psychology Programs
Office of Naval Research
Washington, D.C. 20360

Mr. Melvin J. Feldman
Argonne National Laboratory
P.O. Box 2528
Idaho Falls, ID 83401

Mr. Carl B. Flatau
Accelerator Department
Brookhaven National Laboratory
Upton, NY 11973

Mr. Ray Goertz
Director
Remotely Controlled Engineering Division
Argonne National Laboratory
9800 South Cass Avenue
Argonne, IL 60439

Mr. Donald L. Grisham, J-9
Assistant Group Leader
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, NM 87544

Mr. Robert C. Hamilton
Institute for Defense Analyses
400 Army-Navy Drive
Arlington, VA 22202

Mr. William Hamlett
Sr. Electronics Tech.
Attending Staff Assoc.
Rancho Los Amigos Hospital
7425 Leeds Street
Downey, CA

Mr. Lee Harrison
President
Control Image Corporation
2162 South Jason Street
Denver, CO 80223

Dr. Quentin L. Hartwig
Biological Sciences Communication Project
George Washington University
Suite 700/2000 P Street, N.W.
Washington, D.C. 20036
Present Address:
Dean of Academic Affairs
Lea College
Albert Lea, MN

Mr. J.K. Hawkins
ROBOT Research Corporation
1250 Prospect Street
Suite C-23
LaJolla, CA 92037

Dr. Jack G. Hewitt, Jr.
Department of Electrical Engineering
University of Denver
Denver, CO 80210

Mr. Edwin G. Johnsen
Chief
Equipment and Facilities Branch
Space Nuclear Propulsion Office
U.S. Atomic Energy Commission
Washington, D.C. 20545

Mr. James Jones
Ames Research Center-NASA
Moffett Field, CA 94035

Mr. William N. Kama
Maintenance Design Branch
Behavioral Sciences Laboratory
6570th Aerospace Medical Research Laboratory
Wright-Patterson Air Force Base, OH 45433

Prof. Thomas R. Kane
Department of Mechanical Engineering
Stanford University
Stanford, CA 94305

Mr. Andrew Karchak, Jr.
Rancho Los Amigos Hospital
12826 Hawthorn Street
Downey, CA 90242

Mr. Hector W. Kay
Assistant Executive Director
Committee on Prosthetics Research and Development
National Research Council
2101 Constitution Avenue
Washington, D.C. 20418

Prof.Dr.Ing. Hans Kleinwächter
7850 Lörrach/Baden
Kreuzstrasse 105
West Germany

Dr. John R. Kosorok
Battelle-Northwest
P.O. Box 999
Richland, WA 99352

Mr. James P. Kottenstette
Mechanics Division
Denver Research Institute
University of Denver
Denver, CO 80210

Mr. Alexander Levin
Directorate of Military Technology
Institute of Land Combat
USACDC
Ft. Belvoir, VA 22060

Mr. Paul E. Litteneker
Project Officer
PA & ET/SPERT Project Branch
Projects Division
Idaho Operations Office
U.S. Atomic Anergy Commission
P.O. Box 2108
Idaho Falls, ID 83401

Dr. Charles B. Magee
Professor
Department of Metallurgy
University of Denver
Denver, CO 80210

Mr. J.C. Metteta l
S.I.E.R.S.
108 Av. du Maine
Paris (14), France

Mr. Robert J. Miller
Space Division of North American Rockwell Corp.
12214 Lakewood Blvd.
Downey, CA 90241
(Mail Code — BB98)

Dr. Maynard L. Moe
Department of Electrical Engineering
University of Denver
Denver, CO 80210

Mr. Ord Morgan
Industrial Economics Division
Denver Research Institute
University of Denver
Denver, CO 80210

Mr. Ralph S. Mosher
General Electric Company
Specialty Materials Products Operation
Building 28
One River Road
Schenectady, NY 12305

Dr. Eugene Murphy, Chief
Research and Development Div.
Department of Medicine and Surgery
Veterans Administration
252 Seventh Avenue
New York, NY 10001

Mr. James L. Nevins
Instrumentation Laboratory
Massachusetts Institute of Technology
75 Cambridge Parkway
Cambridge, MA 02139

Dr. Marshall Reich
Chief, Clinical Research
Fitzsimons General Hospital
Denver, CO 80240

Mr. Paul E. Renas
Space Nuclear Propulsion Off.
NASA
Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

Mr. Earl R. Schlissler
Program Manager
Manipulator Programs
Westinghouse Electric Corp.
Underseas Division
Ocean Research and
Engineering Laboratory
Box 1488
Annapolis, MD 21401

Mr. John T. Schwartz
Electronics Division
Denver Research Institute
University of Denver
Denver, CO 80210

Dr. Thomas B. Sheridan
Massachusetts Institute
of Technology
Room 1-110
77 Massachusetts Avenue
Cambridge, MA 02139

Mr. Samuel Snyder
Technology Utilization
Officer
Space Nuclear Propulsion Off.
U.S. Atomic Energy
Commission/NASA
Washington, D.C. 20545

Mr. Richard H. Sprince
NASA
Washington, D.C. 20546

Mr. Robert Swain
Aerojet-General Corporation
3300 Crow Canyon Road
San Ramon, CA

Mr. Fred P. Venditti
Electronics Division
Denver Research Institute
University of Denver
Denver, CO 80210

Mr. Robert Venuti
Assistant Director
for Operations
Denver Research Institute
University of Denver
Denver, CO 80210

Mr. Jean Vertut
Centre D'Etudes Nucleaires
de Saclay
Commissariat a L'Energie
Atomique
Paris, France

Dr. Michael J. Wargo
Dunlap and Associates, Inc.
1454 Cloverfield Blvd.
Santa Monica, CA 90404
Present Address:
Dept. of Mental Hygiene
Fairview State Hospital
Costa Mesa, CA 92626

Mr. John G. Welles
Industrial Economics Division
Denver Research Institute
University of Denver
Denver, CO 80210

Mr. Roy Wirta
Frank H. Krusen Center for
Research and Engineering
Moss Rehabilitation Hospital
12th Street and Tabor Road
Philadelphia, PA 19141

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